Contemporary processes of tunnelling and gullying at Bungonia, Southern Tablelands, New South Wales

Maria Coleman
University of Wollongong

CONTEMPORARY PROCESSES OF TUNNELLING AND GULLYING AT BUNGONIA, SOUTHERN TABLELANDS, NEW SOUTH WALES

A thesis submitted in fulfilment of the requirements for the award

of the degree

MASTER OF SCIENCE (HONOURS)

from

THE UNIVERSITY OF WOLLONGONG

by

Maria Coleman B Env Sc (Honours)

SCHOOL OF GEOSCIENCES

FACULTY OF SCIENCE

May 1996

In my end is my beginning.

T.S.Eliot

DECLARATION

I declare that this thesis is a report of research work carried out by me and has not been submitted in any form for a higher degree at any other university. Information obtained from the published or unpublished work of others has been acknowledged.

Maria Coleman

Maria Coleman

May 1996

ABSTRACT

The results of an investigation into the processes of erosion occurring in the Bungonia District of the Southern Tablelands, NSW Australia are presented in this thesis. The Bungonia District contains numerous examples of erosion gullies which have resulted from processes of tunnelling and gullying. Three erosion sites (*Winston Gully*, Bungonia 2 and Bungonia 3) were investigated in terms of the processes occurring and various physical and chemical soil properties. Large erosion gullies such as *Winston Gully* not only render agricultural land unproductive, but are suspected of contributing large quantities of sediment into the Shoalhaven River Catchment.

Extensive subsurface erosion is occurring at *Winston Gully* within the horizontally bedded lacustrine sediments which were deposited during the Cainozoic Era. This has resulted in the formation of flutes, pinnacles, tunnels and small caves at *Winston Gully*. Sidewall fracturing, slumping and channel scouring are also present to a lesser extent. Subsurface erosion is absent from the Bungonia 2 and Bungonia 3 sites which are under the influence of small scale gullying.

Analysis of the soils indicates that they are composed of kaolinite and illite, with a high percentage of clay and silt. The soil aggregates were found to be unstable when in contact with water due to the lack of organic binding and cementing agents. The exchangeable sodium percentage was calculated to be as high as 47%. The high concentrations of both exchangeable sodium and magnesium are indicative of highly dispersive (sodic) duplex soils. The soils were also found to have a low pH, very low electrical conductivity levels, with exchangeable aluminium present in some samples at non-toxic levels.

The calculated sediment yield (3 800 $t.km^{-2}.yr^{-1}$) indicates that *Winston Gully* is an especially active erosion site. Previous and current erosion control techniques are examined and evaluated, with recommendations for future management strategies given.

ACKNOWLEDGMENTS

Many people have assisted in the preparation of this thesis with helpful discussion, criticism, assistance and support, without whom this thesis would not have been possible. These include:

- Professor John Morrison (University of Wollongong) for his encouragement, guidance, critical comments of drafts, and for providing me with the incentive to finish when he said that "if the thesis is not finished in time you won't be going on holidays".
- Associate Professor Bob Young (University of Wollongong) for initiating the thesis.
- Kevin Cooper and Phil Broadhead (landowners) for allowing access to their properties, relevant reference material and historical information.
- Neil Cooper (Logging and Regional Forestry Manager, ACT Forests) for important reference material.
- Gavin Pyrde (Department of Land and Water Conservation Service NSW, Goulburn Office) for relevant information and introduction to the site.
- Sue Butler and Catherine Lancaster (University of Wollongong) for persisting with me while using the AAS machine.
- Max Perkins (University of Wollongong) for conducting X-Ray Diffraction on the clays.
- David Price (University of Wollongong) for the use of the research lab and equipment.
- Triple J for retaining my sanity in the lab for all those months of work.
- I would especially like to thank both my mother and my husband Terrence Coleman for his assistance in the field, constant support and encouragement.
- Finally, and by no means least, I wish to thank my fellow postgraduate students and field assistance from geography for their interest, assistance, and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF EQUATIONS

1 INTRODUCTION

1.1 INTRODUCTION TO SOIL EROSION

"Soil is one of the world's most valuable assets and frequently it is the richness and fertility of this resource which determine a region's wealth" (Charman and Murphy, 1991, p.3). History provides numerous examples of civilisations that flourished by virtue of their agricultural wealth, only to decline as the fertility of their soils was depleted by unsustainable use. In comparison to the rest of the world, Australian soils are ancient, with the productive topsoil having little depth, leaving it especially vulnerable to erosion as a result of inappropriate land management practices. This is especially pertinent since agricultural products have formed a significant proportion of Australia's Gross National Product (GNP) for much of its recent history. It has only been during the last few decades that the economic and environmental consequences of land degradation have been appreciated, as vast areas of previously productive farmland suffered the effects of different forms of soil erosion. The removal of vegetation cover from agricultural land has resulted in the topsoil becoming exposed to erosive processes such as wind and water (see Chapter 2).

Erosion is the result of various physical and chemical processes acting in combination within the environment. Soil erosion is frequently episodic, with periods of active erosion interspersed with periods of relative stability. The consequences depend upon the frequency and magnitude of the erosion events; the presence or absence of streams or channels; the topography of the landscape; climate; and natural or human features downstream from the erosion site (e.g., road construction) (Edwards *et al*, 1989).

Processes associated with water erosion are dependent upon a variety of interrelated thresholds, both intrinsic and extrinsic. Historically, water erosion was initially classified into stages corresponding with the concentration of surface runoff. "It started with the washing of surface soil (sheet erosion), then rill erosion as the water concentrates into small rivulets, then gully erosion when the eroded channels are larger, and stream bank erosion when rivers or streams are cutting into the banks" (Hudson, 1971, p.38). This classification is no longer adequate, for it ignores the importance of rainsplash as the first stage of water erosion. Erosion by water is more suitably defined as the dislodgment of soil aggregates within a soil profile, which are subsequently transported and deposited elsewhere (Hudson, 1971).

1.2 THE IMPORTANCE OF STUDYING GULLY AND TUNNEL EROSION

Large areas of Australia are affected by both gully and tunnel erosion, resulting in serious land degradation (e.g., removal of topsoil and increased sediment loads of streams and rivers). When surface water is concentrated within channels, the increased energy of the flow can initiate the formation of gullies as the water erodes the soil. Tunnel erosion occurs within permeable soil layers when subsurface flow is concentrated along weak points within the soil, such as cracks or at the boundary with an impermeable soil layer. The processes involved in the formation of gully and tunnel erosion are described in greater detail in Chapter 2.

Gullies change with time as part of the general landscape evolution. Once gullies can be quantitatively described in terms of stages of development, the decision-making process in land and water management will be substantially improved (Heede, 1974).

A number of different mechanisms have been identified as contributing to the formation and continuation of gully development. Gully initiation may result from human activities (anthropogenic influences such as landuse changes), variations in climatic conditions and catastrophic events (fire, earthquakes). In addition, some gullies can form simply as a self-induced adjustment within the landscape, without any evident triggering mechanisms (Edwards *et al*, 1989).

Human activities which initiate gully formation include farming and grazing, or construction (e.g., roads, dams, fences) that may concentrate or alter the flow of water and increase its erosive capacity. The effect of climatic fluctuations such as the frequency, intensity or seasonality of rainfall upon gully formation is less certain. While increased rainfall can lead to increased runoff and erosive potential, it can also result in denser vegetation cover which inhibits erosion. Conversely, lower rainfall results in depleted ground cover, increasing the potential for erosion during intense rainfall events (Edwards *et al*, 1989). Gully formation frequently results from either human activity or climatic factors acting separately or in combination.

The processes responsible for the formation of a gully need to be understood so that appropriate soil conservation measures can be applied. Gully initiation is generally described as the result of incision by surface runoff, with the role of subsurface erosion being disregarded. Subsurface flow and erosion are poorly defined processes, and gullying, when induced by tunnelling, is the major mechanism in badland development (Bocco, 1993).

There is a loss of productive agricultural land due to the effects of gullying. Gullying may also affect the quality of water by increased suspended and dissolved matter concentration, and lowering the pH of the water (Schouten and Rang, 1984).

Tunnel erosion has been a widespread problem in agricultural land of Australia for over a century (Crouch, 1983). Tunnel erosion was first noted in Victoria in the early 1900s, and the NSW Soil Conservation Service noticed its occurrence in NSW during the 1920s (Boucher and Powell, 1994). Since the report by Newman and Phillips (1957), tunnel erosion has assumed greater importance in the assessment of the affected areas, and the implementation of control measures has become a major concern of government organisations.

Tunnel erosion is a form of soil degradation which, once initiated, is difficult to control due to its widespread formation and consequences (Crouch *et al*, 1986). The majority of studies have been concerned with the origin and causes of tunnelling, and its role in gully development. Martin-Penela (1994) found that there were few studies devoted to the interaction between tunnelling and gullying, and the influence of human activities upon their development.

Crouch *et al* (1986) noted that tunnels generally share similar physical characteristics, but the mechanism responsible for their formation varies from site to site. Controlling tunnel erosion is especially difficult, since the subsurface transportation of water cannot be limited to non-erosive velocities, and the physical and chemical properties of the soil cannot be altered easily. Revegetating the soil surface generally does not solve the problem of subsurface erosion.

Floyd (1974) reported that tunnel erosion is found to be associated with duplex soils with an impermeable B horizon and poor vegetation cover. In Australia, the most susceptible soils are those in the duplex category and the solonetzic, solodised solnetzic, solodic, podzolic and red-brown earth Great Soil Groups (Boucher, 1990).

There is general agreement on the formation of tunnel erosion (Jones, 1971). The causes include:

1. a susceptibility of the soil to crack during dry periods (high silt/clay content, and a high percentage of swelling clays);

2. periodic, high intensity rainfall and devegetation;

3. an erodible layer above the subsurface horizon, high exchangeable sodium percentage (ESP) and high base exchange capacity or soluble salts (alkaline soils);

4. a biotic break-up of soil and a relatively impermeable subsurface horizon; and

5. a steep hydraulic gradient.

Factors which determine the extent and magnitude of gullying and tunnelling are summarised in Table 1.1.

Table 1.1: Summary of the factors contributing to gully and tunnel erosion (modified from Edwards *et al*, 1989).

Form of Erosion	Factors Determining Extent
Gully	Catchment size, soil type, topography, land use and management, predisposing features such as tracks and roads, climate and catastrophic events, landform history.
Tunnel	Soil type (cracking and dispersibility), ground cover, climate.

Sodicity (or the potential for dispersion) is defined in terms of a soils ESP and the sodium absorption ratio (SAR) of the solution. In Australia, sodic soils have been defined as soils with an ESP greater than 6, and a SAR greater than 3 (see Chapter 2). Environmental problems frequently encountered with sodic soils include land degradation, high vulnerability to erosion and severe water quality problems. There is limited information available for farmers in minimising the effects of sodicity due to the lack of awareness, identification of the problem, and insufficient information concerning suitable management strategies (Naidu *et al*, 1993).

1.3 GULLY EROSION ON THE NSW SOUTHERN TABLELANDS

The NSW Southern Tablelands region has basically existed in its current form since the Eocene, with regional topography influenced by Quaternary erosive processes (Wray *et al*, 1993). During the late Holocene, alluviation in the valleys of the Southern Tablelands has been recognised as evidence of erosion, induced by either climatic change or an intensification of Aboriginal landuse practices. The latter possibly is suggested from studies of alluvial stratigraphy of Wangrah Creek near Canberra by Prosser (1991). Young *et al* (1986), however, established that this hypothesis does not apply throughout the entire area. This is based upon a study of alluvial chronologies which showed no clustering of dates. From this, Young *et al* (1986) concluded that the alluviation was controlled by local, rather than regional factors.

Hughes and Sullivan (1981) suggested that Aboriginal firing regimes were responsible for episodic erosion and deposition at rates which greatly exceed those under natural firing. The geomorphic effects that can result from landuse practices involving the disturbance or removal of vegetation, cultivation and grazing are well documented. In contrast, the activities of Aboriginals are generally seen as having had little geomorphic effect. Hughes and Sullivan (1981) contend that it is possible that Aboriginal burning in the dry sclerophyll forest landscape of eastern Australia could have been the major, if not sole, cause of episodic erosion and depositional events.

Erosion gullies within the Southern Tablelands have been identified by Sydney Water as the principal source of sediment entering the Shoalhaven River (G. Pyrde, Department of Land and Water Conservation (Goulburn), *pers. comm.,* 1995). Increased sediment loads results in siltation and a decrease in water quality. The majority of valleys in the Southern Tablelands currently contain erosion gullies up to 5 metres in depth (K. Cooper, land owner, *pers. comm.*, 1996).

Prior to European settlement there were no continuous channels, but a series of deep pools referred to as "chains of ponds" as stated by Eyles (1977). During the period of European settlement there have been major changes in geomorphic processes, resulting in major land degradation throughout the Southern Tablelands (Prosser, 1991). While human interference is one of the external influences capable of effecting gully development, it is neither the sole instigator nor pre-requisite for the initiation of gully development (Smith, 1982).

The growth of gullies is encouraged by bad practices in ploughing, overgrazing, incorrect planning of roads, removal of vegetation cover, surface drainage of rain-water, and irrigation (Zachar, 1982). Gully growth is attributed to agricultural mismanagement which has accelerated the natural process.

1.4 REGIONAL SETTING OF BUNGONIA

1.4.1 Location and Topography

The Bungonia District is located approximately 30 km SE of the city of Goulburn on the NSW Southern Tablelands (Figure 1.1). Bungonia is situated on the Lower Shoalhaven Plain (500 to

700 m elevation), consisting of broad shallow valleys in rolling hills (Craft, 1932). The primary study site of *Winston Gully* is situated at the head of Limekiln Creek on the properties of *Inverary Park* and *Inverary*. Limekiln Creek originates on basalt hillsides falling northward to a junction with Inverary Creek, which forms part of the Shoalhaven River Catchment (Wray, 1991).

The topography of the Bungonia District was previously attributed to peneplanation during the Miocene, uplift during the Tertiary and incising by the Shoalhaven River during the Pleistocene. Wellman (1974), however, reported that results of Potassium/Argon dating conducted on basalt flows at *Inverary Park* indicate that the principal topographic features had been well developed by the Eocene (46.1 Ma).

Wray (1991) found that changes in sediment type and source within the catchment were common during the Cainozoic, with the timing of these changes during the Late Quaternary not correlating with observations from other areas of the Southern Tablelands. He also suggested that changes in the hydrological regime, especially climate, were not necessarily the major cause of the changes in the stratigraphic record at *Inverary Park*. This conclusion contradicts commonly accepted models of landscape development (e.g., Davisian and Penck models).

The complex stratigraphic record at *Inverary Park* is the result of significant geomorphic changes which occurred during the Cainozoic, and minor modifications to the landsurface during the Late Eocene. This conclusion is derived from the relationship of the Late Eocene Reevesdale Basalt, with the younger Late Tertiary and Quaternary alluvial deposits. The general form of the modern landscape was well developed prior to the basalt eruption, the modern drainage system was established by the Late Eocene and lastly, significant alluvial erosion and aggradation had occurred prior to the basalt eruption with the formation of the sub-basaltic topography. Consequently, the Reevesdale Basalt divides the Cainozoic geomorphic history of the region into three distinct phases, namely pre-basaltic, intra-basaltic, and post-basaltic (Wray, 1991).

Wray (1991) concluded that average rates of erosion (post-basaltic) have been very slow (i.e., approximately 0.65 m per million years), and that the majority of the post-basaltic erosion has occurred during the Late Pleistocene and Holocene with the reworking of older sediments.

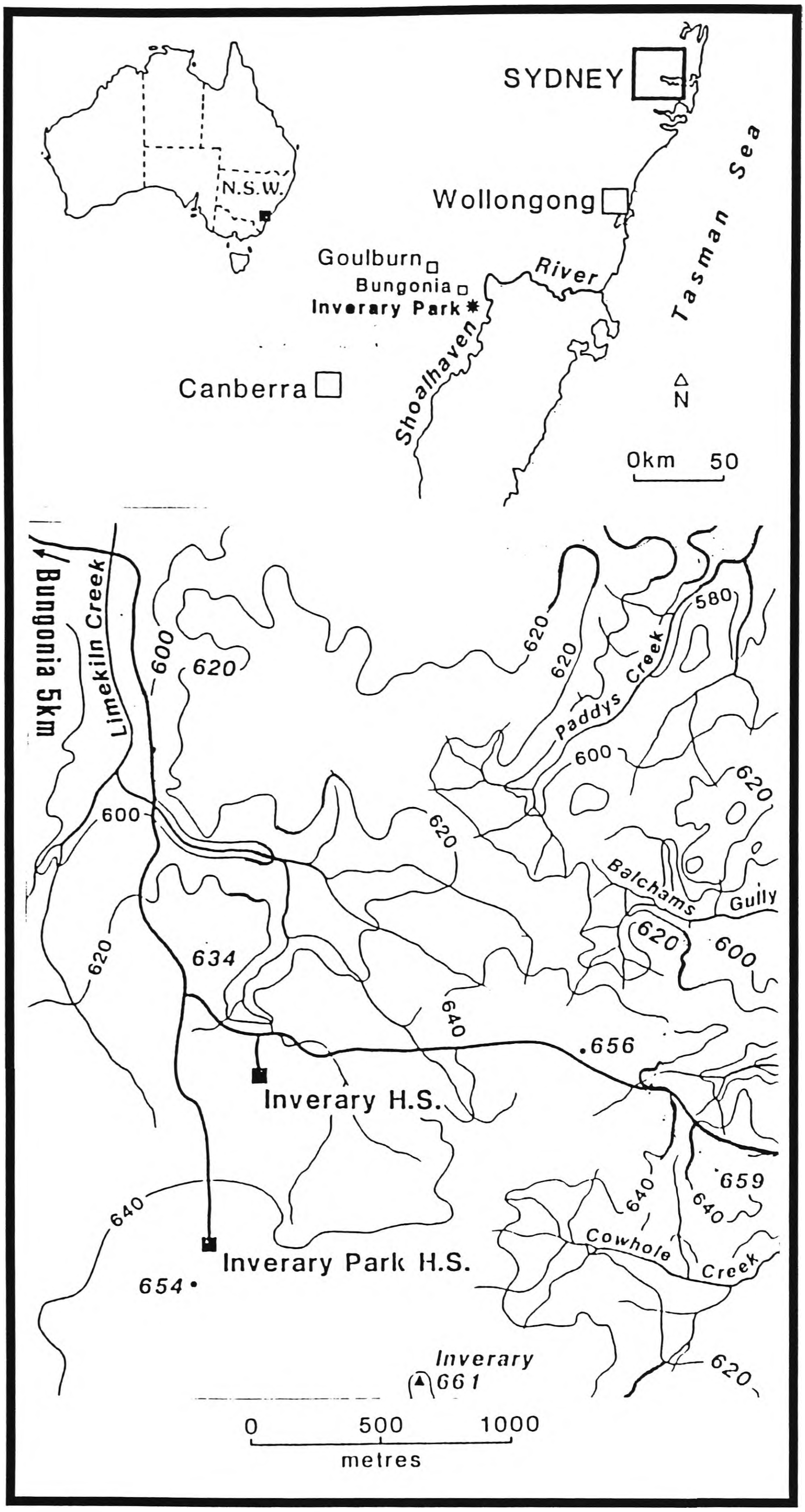

Figure 1.1: Location map of Bungonia and the properties of *Inverary Park* and *Inverary* (modified from Wray *et al*, 1993).

1.4.2 Climate

The climate of the Bungonia District is classified as humid temperate (Köppen's Cfb). The mean annual rainfall at *Inverary Park* is 670 mm, with the majority of the rainfall occurring in winter

(June to October) (K. Cooper, *pers. comm.*, 1996). The mean temperature of the coldest month for Goulburn is 7.2°C, and a mean temperature of the hottest month of 18.9°C (Bureau of Meteorology, 1988). It must be remembered, however, that as the landforms within the area date from the Early Tertiary, they were initiated when the climate was significantly different to the present (Wray *et al*, 1993).

1.4.3 Vegetation

Bungonia is dominated by various species of Eucalypts, native pines and grasses. Large areas of forest were cleared during the initial period of European settlement for farming and grazing, but extensive stands of dry Sclerophyll forest still remain in the Shoalhaven River Gorge. Wray (1991) noted that while there is no correlation between the natural vegetation and rock type, the quartz-rich Ordovician and Devonian sediments are timbered with little undergrowth, while the shale, limestone and sandstone areas may contain dense undergrowth.

1.4.4 Geology

The Bungonia District lies on the boundaries of the Palaeozoic Lachlan Fold Belt (north-south trending Lachlan Geosyncline) and the Permo-Triassic Sydney Basin. The Lachlan Geosyncline extends from Victoria through to northern NSW, where it is overlain by the Great Artesian Basin sequence (Packham, 1969).

Bungonia is made up of greywackes and cherts from the Tallong Beds which were deposited during the Ordovician when the sediments were being folded. During the Upper Silurian, the Bungonia Limestone and shallow water sediments were deposited, with active volcanism during the Devonian. These rocks were then intruded by the granite of the Devonian Marulan Batholith, and folded once again. The folding between Goulburn and Bungonia developed into a NS syncline-anticline-syncline feature (Naylor, 1950).

During the Permian and Triassic the Sydney Basin sedimentary structures were deposited, with early extensions along the east of the Shoalhaven River and small deposits around Bungonia on the Basin Margin. During the Tertiary basaltic volcanism, fluviatile and lacustrine deposition and extensive duricrusting occurred, and alluvial and colluvial deposition took place during the Quaternary (Wray, 1991).

1.4.5 Kaolinised and Post-Basaltic Sands and Clays

The intra-basaltic sediment units at *Inverary Park* are generally composed of laminated clays derived from the reworking of kaolinised bedrock within the catchment boundaries into a lake formed by basalt daming. Wray (1991) stated that these laminated clays had been transported and re-weathered *in situ* underlying the basalt after extrusion. The laminated clays visible at the head of *Winston Gully* belong to this sequence and are highly weathered, with extensive clay drapes and skins covering the gully walls. Deposited between the lacustrine sediments and the Ordovician bedrock is a stratified layer of basal (i.e., bedrock) gravel, indicating that the lacustrine sediments infilled a pre-lake gully eroded into the bedrock.

The Eocene upper valley lake disappeared due to nickpoint retreat and large scale episodes of erosion resulted in the cut and fill deposition of Post-Lake sands, clays and gravels (the terminology of Wray, 1991 and Wray *et al*, 1993). This stratigraphic unit is extensively gullied and exposed along Limekiln Creek.

The Holocene Black Clay is one of the most extensive stratigraphic units. It is derived from basalt, and was deposited prior to contemporary gullying. This Black Clay overlays the Quaternary Orange Sand, which in turn overlays lacustrine kaolin clays in some areas (Figure 1.2). The dry texture of the clay changes from being quite dense and compact to a silty-sandy composition.

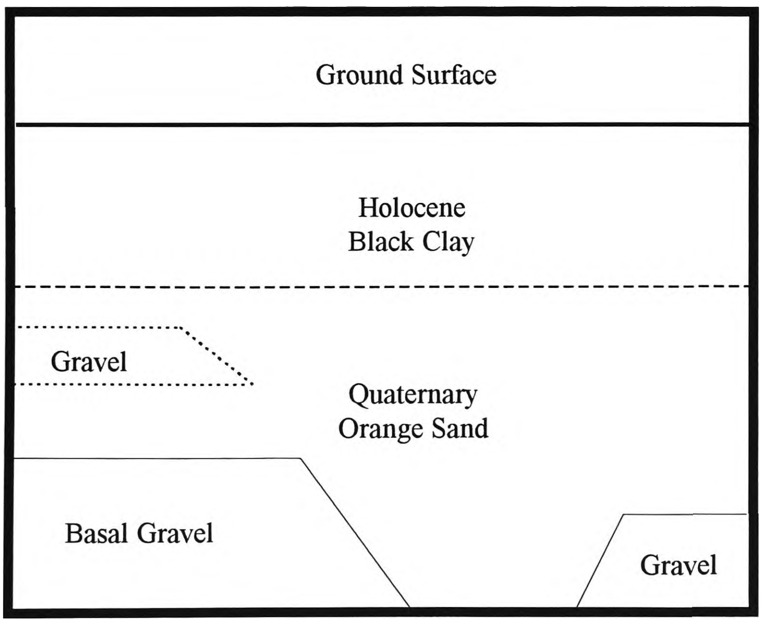

Figure 1.2: Stratigraphic unit showing the Holocene Black Clay and Quaternary Orange Sand overlaying the Basal Gravels along the west bank of Limekiln Creek (Wray, 1991). Not drawn to scale.

The Quaternary Orange Sands overlay Mottled Clays and Colluvial Mantles along Limekiln Creek. Wray (1991) suggests that these sands have originated from within the catchment of the Lower Valley due to the lack of evidence within the sedimentary units that the Sand had been transported from the Upper Valley. The Mottled Clays are overlain by several colluvial fan deposits along Limekiln Creek. These non-laminated Mottled Clays have been reworked from the Upper Valley Lacustrine and Post-Lake sediments.

1.5 SHOALHAVEN RIVER CATCHMENT PROTECTION SCHEME AND INVERARY CREEK LANDCARE

The stabilisation and rehabilitation of gullies such as *Winston Gully* has become an important issue of concern for the Shoalhaven River Catchment Protection Scheme (SRCPS) and Landcare. Since 1993 the major goal of SRCPS and Inverary Creek Landcare at Bungonia is to control the flow of surface and subsurface water. Due to the profound dispersibility of the soil, earthworks are an uneconomical and unrealistic approach to rehabilitating the *Winston Gully* site. A program of extensive keyline ripping, mounding and tree planting in order to revegetate and rehabilitate Inverary and Limekiln Creeks was commenced in mid-1995 (Plate 1.1). This program has been supported by funding from the Total Catchment Management Enhancement (NSW Government) and SRCPS. ACT Forests has also provided the Landcare group with *Pinus radiata* seedlings and technical support, including soil surveying and management plans.

By late 1995, the initial planting of *Pinus radiata* along key lines in an area of 20 hectares surrounding the gully was complete. The landowners (P. Broadhead and K. Cooper) are keen to proceed with a 10 year planting program of 121 hectares into an Agroforestry venture. If successful, an extra 5 to 10 hectares per year of Eucalypt and Casuarina species would be planted in the future along with more keyline ripping and hand seeding of the gully's banks.

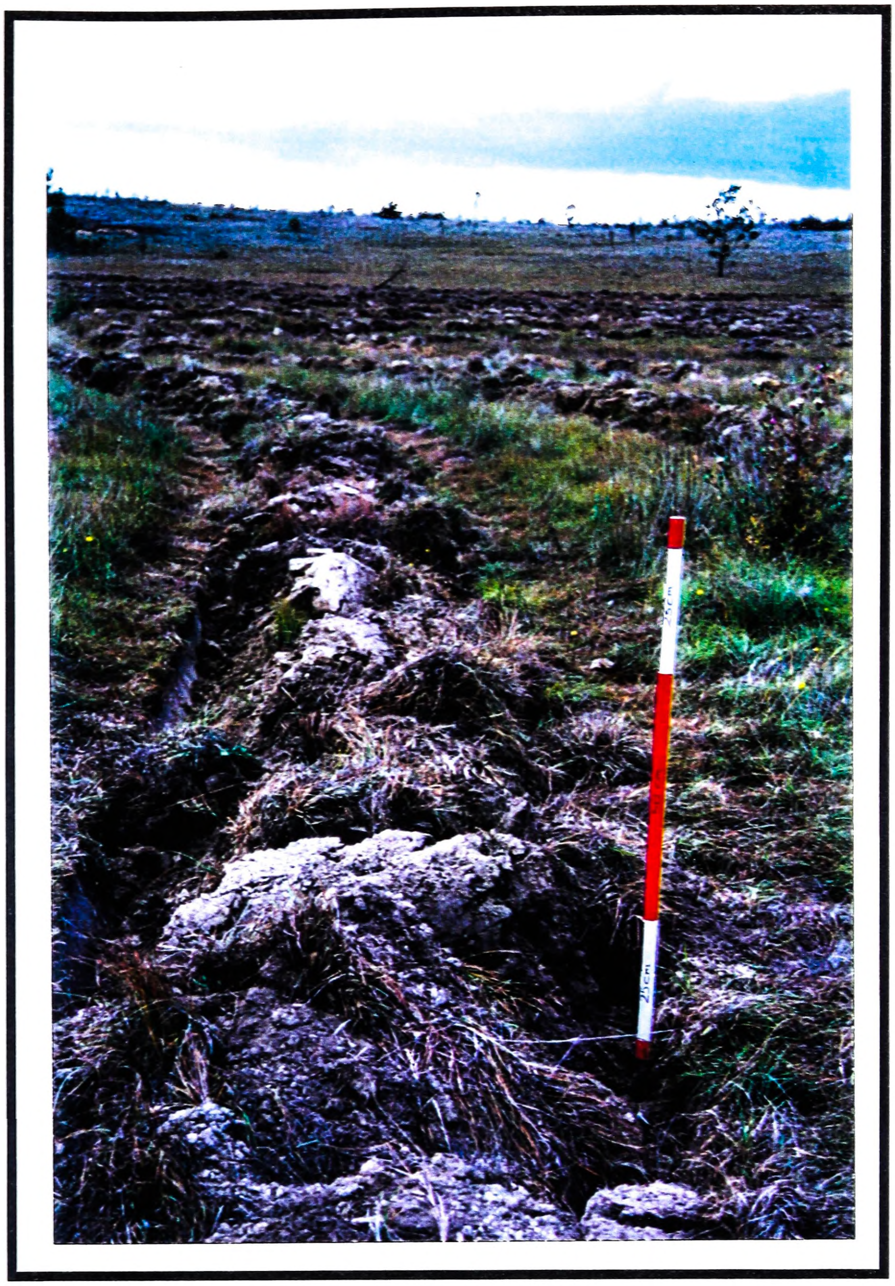

Plate 1.1: Keyline ripping conducted at *Winston Gully*, Bungonia.

The Department of Land and Water Conservation (Goulburn) believes that erosion sites such as *Winston Gully* are significant contributors to the quantity of sediment entering the Shoalhaven River (G. Pyrde, *pers. comm.*, 1995). At *Winston Gully*, the Department has constructed a number of sediment traps within the gully's stream bed in order to control and limit the mobilisation of sediment within the gully during high rainfall events. This is discussed further in Chapter 5.

1.6 AIMS OF THE STUDY

While the problem of tunnelling and gullying is widespread throughout soils of the Southern Tablelands, the erosion mechanisms and rates are poorly understood. This site was chosen because of the extensive gullying and tunnelling present, and a detailed geomorphological study of Bungonia had been completed by Wray (1991). This study involved a detailed field and laboratory assessment of the physical and chemical characteristics of the soils at the Bungonia study site.

The following objectives were ascertained within this study:

- To identify and describe the contemporary processes and erosive mechanisms occurring within the sites.
- A chemical analysis of the soils to determine the sodicity and other chemical characteristics, and how these may influence erosion processes.
- A physical analysis of the soils to determine the relationship to the erosive processes present.
- To determine the erosion rates within *Winston Gully*.
- To recommend soil management strategies for controlling the tunnelling and gullying present at *Winston Gully*.

2 PREVIOUS STUDIES ON GULLYING, TUNNELLING AND SODIC SOILS

2.1 GULLY EROSION

2.1.1 Introduction

Gullies are not restricted to one specific soil type, climate or geographical area (Fitzpatrick *et al*, 1995). The occurrence and intensity of gully erosion tends to be encouraged by dispersive clay (sodic) soils and inappropriate farming techniques (Boucher and Powell, 1994; Graham, 1984). Gullies are of great concern to landholders due to the quantity of soil lost from productive land during rainfall events.

Campbell (1989) stated that gullies form in the following three topographic settings:

- Alluvial-fill deposits in preformed valleys.
- Gullies cut in bedrock on slopes or valley sides.
- Gullies developing as headward extensions of a drainage system on undissected upland surfaces.

2.1.2 Definition of Rills and Gullies

The primary distinction between a rill and a gully is the depth. A rill is shallow enough that it can be smoothed by ordinary tillage, while a gully is too deep to be demolished by normal tillage operations (Poesen and Govers, 1990). Rills play a major role in the mobilisation of sediment and water transfer to channels. The initiation of rills requires certain flow concentration and hydraulic conditions to occur (Bowyer-Bower and Bryan, 1986). Rills can ultimately develop into gullies.

Gullies have been defined as extended erosion channels with steep vertical sides, either "U" or "V" shape cross-sections, whose width and depth do not allow normal tillage. Gullies form under the influence of a geomorphic thresholds such as climatic, anthropogenic (extrinsic) or inherent to the gully system itself (intrinsic). Gully formation frequently occurs in the absence of vegetation, associated with surface and subsurface flow, resulting in a breakdown of the equilibrium between process and form in a water course (Bocco, 1991; Boucher and Powell, 1994; Butzer, 1976;

Graham, 1984). Characteristic gully forms include linear, bulbous, dendritic, trellis, parallel and compound. Different types of gully erosion are illustrated in Figure 2.1.

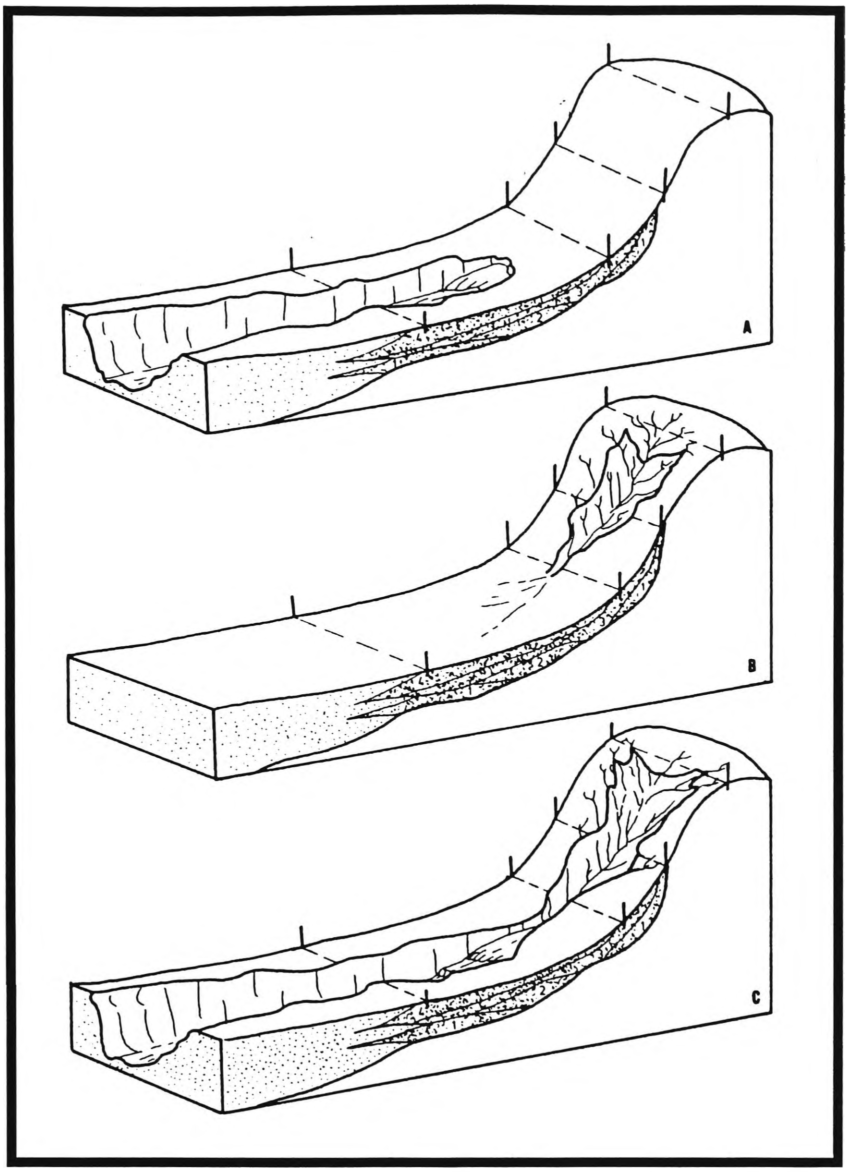

Figure 2.1: Three different types of gully erosion. Type A: headward expansion; type B: overland flow; type C: a combination of types A and B with seepage erosion downslope and concentrated overland flow upslope (de Oliveira, 1989).

2.1.3 Factors Governing Gully Erosion

The growth of a gully is dependent upon the channel cross-section, water velocity and sediment load. Erosion rates increase when the water flow has sufficient energy to transport the fallen debris from the base of the gully walls to downstream sites. Soil strength, permeability, thickness, and structural features influence gully wall geometry and the rate of erosion. The position of the water table influences gully wall failure since soil strength decreases with increasing moisture content, and the increased unit weight of the soil mass with greater water content exerts more force (Bradford *et al*, 1978).

Another major factor affecting gully erosion is the nature of the soil and the bedrock, the resistance of which is characterised by the critical water velocity required to cause gullying. The intensity of gully erosion decreases in the following direction: soil over sandy substrata→soil over loess, clayey and heavy loam substrata→skeleton soils. The intensity is also strongly influenced by the thickness of loose, easily erodible or moderately erodible sediments (Zachar, 1982).

Climate is the most important factor governing gully erosion, since it determines the intensity of erosion and the rate and type of plant growth (Zachar, 1982). The influence of tunnelling on the origins and development of gullies has been recognised in different climatic zones, but is more significant in arid and semi-arid regions (Martin-Penela, 1994).

2.1.4 Gully Formation Processes

Processes which influence gully sidewall and headwall development include bank undercutting, surface flow, subsurface flow, rainsplash and soil dispersion, fluting, frost action, and wind erosion. On-slope processes include weathering, mass movement, surface and sub-surface erosion processes, on-slope deposition and stabilisation by vegetation. Process interactions influence erosion rates and control the style of morphological development (Harvey, 1992).

Gullies are formed by rapid erosion of soils from permanent drainage channels. During rainfall events, gullies usually cut headward, widen and deepen in unconsolidated parent materials. Subsurface tunnelling can also be associated with headward erosion and has been widely recognised as a mechanism of gully sidewall erosion (Butzer, 1976; Crouch, 1983). Figure 2.2 illustrates four gully head types formed as a result of different processes occurring within an environment.

Surface erosion by overland flow and rill flow is often viewed as the primary mechanism in gully development. Swanson *et al* (1989), however, reviewed numerous studies which showed that subsurface erosion was an important factor in the extension of gully networks. Subsurface erosion proceeds by true soil piping and tunnelling. True soil piping is the excavation of unconsolidated material by seepage force under the conditions of a positive hydraulic head. Once an open conduit is formed, expansion proceeds by turbulent concentrated flow, termed "tunnel gully erosion". Leopold and Miller (1956, cited in Swanson *et al*, 1989), were the first to recognise subsurface erosion as a mechanism for headward extension of existing gullies, and Jones (1971) recognised the role of soil piping in stream channel initiation.

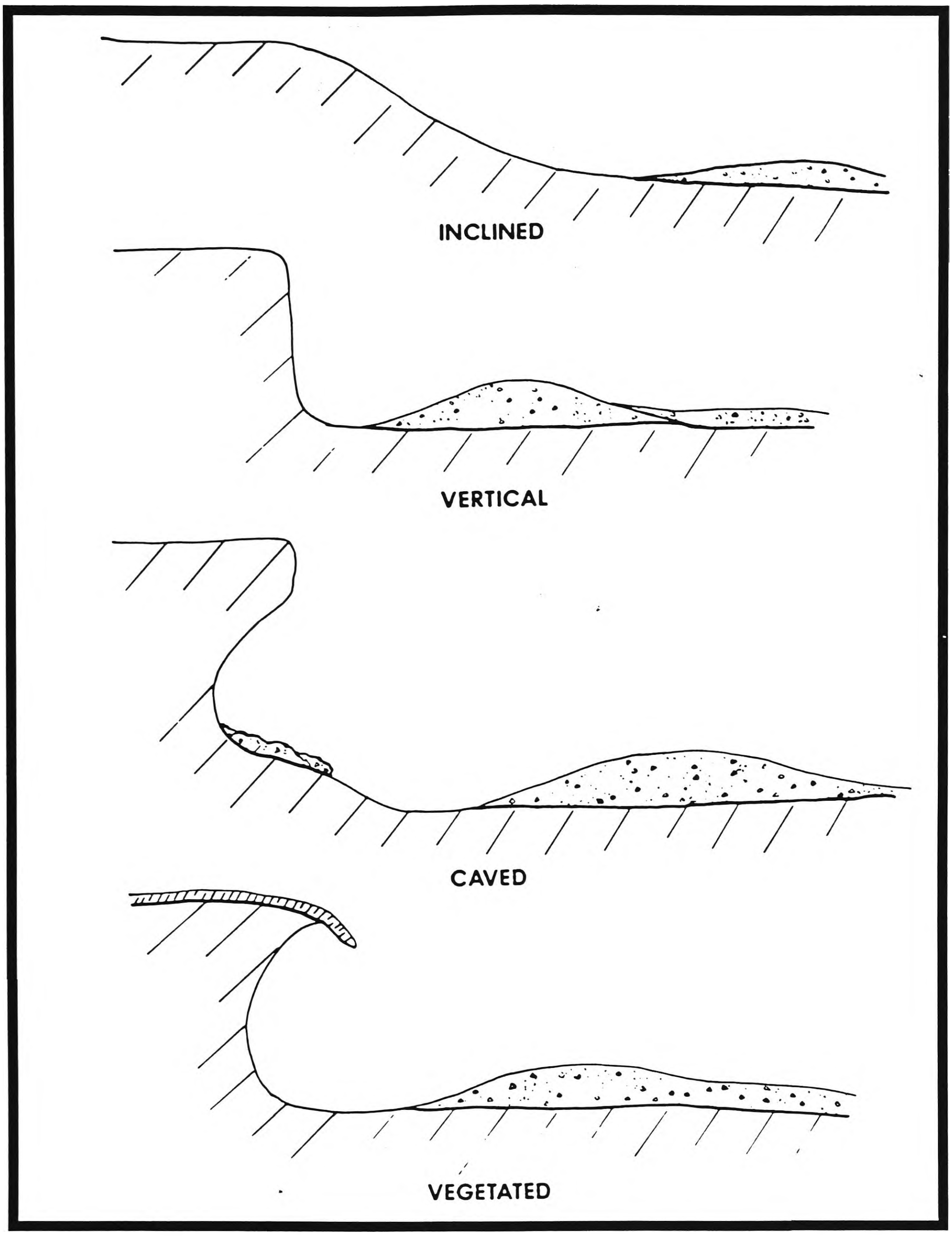

Figure 2.2: Four gully head types associated with different processes (Charman and Murphy, 1991).

Once formed, the gully can continue to work backwards developing along tributaries up the hill, through the continual slumping of the subsoil. The gully will cut into the bed until it reaches equilibrium with the environment, and stabilises (Leeper, 1967). Stages of gully development have been described in detail by Woodruff (1935), Ireland *et al* (1939), and Daniels (1966, cited in Bradford *et al*, 1978). It has become generally accepted that gully erosion occurs when the energy of the flow is sufficient to erode the sediment comprising the stream bed.

2.1.5 Gully Control Measures

2.1.5.1 Filling, Reshaping and Revegetating the Gully

Gully filling is an appropriate method of control when gullies are shallow (1–3 m in depth) and subsurface erosion is not the dominant sidewall or headwall process. The first stage in filling a gully involves scraping and conserving the topsoil. The subsoil is then pushed into the gully, the edges smoothed and the topsoil spread back over the reworked area. The final stage involves revegetating the site (Graham, 1984).

The steps involved in gully reshaping are similar to filling a gully. Instead of filling the gully, the active sections of the gully are bulldozed to a more stable and less erosive angle. The topsoil is then pushed over the reshaped area and revegetated (Graham, 1984). Where the flow of water cannot be diverted from the gully, the stability of the gully is dependent upon the quick establishment of vegetation cover (Crouch *et al*, 1987).

The primary purpose of revegetation is to stabilise the gully walls. Thompson and Troeh (1973) reported that U-shaped gullies need to be reshaped due to the difficulties in getting vegetation to grow on vertical gully walls. The disturbance of soils which are high in soluble salts (such as sodium) by mechanical means can increase in the quantity of salts being leached from the soil. The gully sides will stabilise as vegetation becomes established within the gully floor and sidewalls (Heede, 1974). To successfully stabilise a gully by revegetation, the vegetation must:

- be easily propagated;
- be able to withstand both dry and very wet conditions;
- be fast growing in infertile soil;
- have a dense vigorous root mat;
- have stems that will not induce excessive turbulence and divert flows; and
- have no potential of becoming a weed (Crouch *et al*, 1987).

2.1.5.2 Gully Control Structures

Gully control structures are used as a complement to filling, reshaping and revegetating, or when there are uneconomical or nonviable options available. Banks and dams are constructed within the catchment to reduce peak flows and divert water away from gullied areas. Control dams are constructed either within the gully or upstream of the gully head in order to reduce peak flow over the headwall and within the gully channel. Dams constructed upstream of the gully head reduce the headwall advance by collecting and diverting overland flows. In some gullies the structures are built within the gully, which is useful in 'drowning' the head, preventing the water from cascading over the headwall (Graham, 1984). Such erosion control structures have proven to be a successful and relatively inexpensive method of stabilising erosion gullies (Crouch *et al*, 1984) in the absence of subsurface erosion.

Even when gullies are filled or reshaped, there remains the problem of conveying the water from the drainage line to the gully floor. Flumes are designed to transport water to the floor of the gully without causing further erosion of the gully walls. Sediment traps are installed in gullies to raise the floor of the gully and to reduce the sediment loss from the system overall. Water behind the traps allows eroded sediment to settle and fill the dam (Graham, 1984).

2.2 TUNNEL EROSION

2.2.1 Introduction

Tunnelling is defined as a process of erosion involving the removal of subsurface soil through hydraulic action. While tunnelling is frequently associated with arid landscapes and saline soils (solonetzic karst), it is present in a wide variety of climatic regions. Tunnel erosion also occurs in cold (thermo-karst) and warm (loamy karst) regions, with sporadic occurrences also occurring in regions of abundant rainfall (clastic karst) on non-saline soils (Jones, 1971; Zachar, 1982).

Tunnels form in zones of high infiltration which allow water to move freely. These include tree stump holes, soil cracks, surface depressions, animal burrows, contour furrows, and dispersive soils (Boucher and Powell, 1994; Crouch, 1976). The concentration of water causes localised saturation of the underlying B horizon, thus contributing to the initiation of tunnelling (Crouch, 1976).

Active tunnel development appears to be associated with drought periods and increased local infiltration when the rain falls on soil with little or no ground cover (Boucher, 1990; Boucher and Powell, 1994). Studies conducted in Victoria and NSW indicate that tunnelling occurs in both solodic and solonetzic soils (CSIRO, 1983). In Victoria, tunnelling occurs in areas with a loamy A horizon and a clayey B horizon, consisting of high dispersibility of subsurface soil during rainfall events (Boucher and Powell, 1994).

2.2.2 Soil Factors Influencing Tunnel Erosion

2.2.2.1 Cracking

Cracking of the topsoil occurs when the A horizon is exposed to the climatic conditions of that region. Cracking (due to natural and/or anthropogenic causes) within the surface soil layer allows water to enter the subsurface soil layers (B horizon) of a dry soil without encumbrance. The water then transports dispersed soil particles, resulting in the formation of tunnels (Crouch, 1976).

2.2.2.2 Dispersion

A common factor of many regions which have tunnel erosion is their dispersive soils. Dispersion in soils occurs when soil aggregates break down in the presence of water, which transports the soil particles elsewhere. Eventually the soil particles are trapped by pore blockage reducing the soil permeability (Crouch, 1976). The decrease in soil permeability promotes the movement of water along cracks within the soil, resulting in the advancement of tunnel erosion (Crouch *et al*, 1986).

Dispersion is associated with the soils ESP, which is dependent on the ionic concentration of the soil solution and clay type. The dispersibility of clays (aluminosilicate minerals) generally increases with the presence of adsorbed sodium (Barzegar *et al*, 1994). Dispersion results from the repulsive forces between clay particles due to diffuse layer interaction, or the separation of clay particles by mechanical energy (Barzegar *et al*, 1994; Chorom *et al*, 1994).

Clays disperse at high ESP values; however, at lower ESP values energy is required for dispersion. Raindrops transfer energy to the soil surface, causing clay dispersion to take place at lower ESP levels than required for dispersion within the soil body. The infiltration rate (which is more sensitive to the presence of sodium than hydraulic conductivity) is reduced by crust formation, which results in increased runoff and erosion (Sumner, 1993).

Swelling caused by the rapid entry of water into the outer layers of aggregates and the destruction of particle-to-particle bonds are commonly given as the reasons for the breakdown of aggregates into smaller particles. If these smaller particles are compounds of ultimate particles, this is known as slaking. Whether or not these microaggregates disperse because of the swelling forces, slaking is the first step in the degradation of soil structure (Collis-George and Lal, 1971).

Sumner (1993) and Churchman *et al* (1995) found that soil pH also influences the dispersion potential by changing the net negative charge on the soil components. Depending on the clay mineralogy and oxide content, soils may exhibit a net negative or positive charge at high or low pH respectively (Chorom *et al*, 1994). A rise in pH in the long term would promote stabilisation of soil aggregates by increasing biological activity and producing iron and aluminium polycations (Rengasamy and Olsson, 1991).

2.2.2.3 Weakening of Bonds Between Particles

The steps involved in the dispersion of soil colloids are a weakening of the bonds between particles, followed by the separation of particles by the application of a small force. Bonding between particles may be due to cementing (by oxides, silicates or carbonates), electrochemical forces or organic matter. Cementing agents are found to be relatively insoluble in water, providing a permanent bond between particles, whereas the electrochemical force acting upon clay particles can be altered significantly in a short period of time (Crouch, 1976).

2.2.2.4 Electrochemical Forces

Within a constrained system, five forces will act upon a clay particle in suspension (Crouch, 1976). These forces are:

- Van de Waals's Forces, which are attractive;
- the attractive forces between the opposite charges;
- the attractive forces due to the Coulombic attraction of two adjacent plates to the intervening layer of positive ions;

- electrostatic repulsive forces due to Coulomb's law of interaction between charges; and
- repulsive forces due to the hydration of exchangeable ions.

The major exchangeable cations in soils are calcium, magnesium, potassium and sodium. Potassium, magnesium and calcium have been shown by Brooks *et al* (1956, cited in Crouch, 1976), to have similar effects on the stability of soil structure. Reeve *et al* (1954, cited in Crouch, 1976), found that the effect of exchangeable potassium on permeability was slight compared to the effect of sodium, while Bakker *et al* (1973, cited in Crouch, 1976), demonstrated that a magnesium saturated soil was more susceptible to dispersion than a calcium saturated soil. An increase in sodium ions on the exchange complex increased the dispersibility of both pure clay systems and field situations, with tunnelled soils usually having high ESP values (Crouch, 1976).

Gombeer and D'Hoore (1973, cited in Crouch, 1976), found that clay mobility decreased with high exchangeable aluminium levels at low pH. The valency of cations (including aluminium) is important, aluminium may act as a cement and affect the exchange complex. A few "cement type bonds" between clay plates at points of closest contact can reduce the swelling characteristics of clays, and possibly reduce the degree of dispersion.

The dispersion of soils in laboratory situations has been shown to be dependent upon the concentration of ions in the external solution. Soil aggregates disperse more readily in solutions of low ion concentration. The maximum soil/water ratio at which soils disperse is a criterion for measuring a soil's susceptibility to dispersion. The degree of slaking is dependent upon an increase in the concentration of cations as the wetting front moves into an aggregate (Crouch, 1976).

2.2.2.5 Organic Matter

Organic matter can either increase or decrease the dispersiblitity of the soil. Emerson and Smith (1970, cited in Crouch, 1976), demonstrated that leaves from Eucalypt species increased the soil to water ratio at which dispersion occurs by reducing the attractive forces between the clay particles. Organic matter of low molecular weight in the presence of clay particles causes dispersion, while organic matter of higher molecular weight will cause clay particles to flocculate. Aggregation of the clay particles is promoted when high levels of organic material is being actively turned over by biotic activity. As organic matter levels decrease, soils often become sensitized to sodium due to the charge generating contributions of the broken bonds on the remaining organic fragments, leading to increased dispersibility of the clay (Sumner, 1993).

Organic binding agents follow into three groups, namely:

1. Transient Binding Agents, which are decomposed rapidly by microorganisms. The main group is polysaccharides, microbial and those associated with roots and microbial biomass in the rhizosphere. These polysaccharides are produced and decompose rapidly, and are transiently stable. Microorganisms produce exocellular mucilages or gums which act as glues in the soil aggregates (Tisdall and Oades, 1982).

2. Temporary Binding Agents, consisting of roots and fungal hyphae which build up in the soil very quickly, persisting for months or years. The binding agents stabilise macroaggregates (> 250 μm diameter) due to the agents being relatively large and growing in large pores in soil (Tisdall and Oades, 1982).

3. Persistent Binding Agents, consisting of degraded aromatic humic components, usually associated with amorphous iron, aluminium and aluminosilicates. They include complexes of clay-polyvalent metal-organic matter (C–P–OM). Strongly sorbed polymers such as 'some' polysaccharides and organic materials stabilise by association with metals are also included in this group (Tisdall and Oades, 1982).

2.2.3 Processes Association with Tunnel Formation

Subsurface erosion is a significant geomorphic agent in the development of gullies. The movement of subsurface water appears to take place as either a sheet of water soaking through the soil, or as a linear flow along a point of weakness in the sediment. This can occur along pore or bed directions, joints, animal holes, or plant roots (Berry, 1970).

Tunnel erosion develops slowly in its initial stages, but quickly accelerates as the tunnels reach the highly erodible subsoils. Therefore, as the tunnelling expands in severity and the land deteriorates, controlling the problem becomes difficult and sometimes impossible (Newman and Phillips, 1957). Crouch (1983) found that where tunnels were present at the gully head, the rate of headward growth was more than 5 times greater than for non-tunnelled gully heads.

Major factors leading to tunnel erosion include a variable rainfall, soil cracking, reduction in ground cover, a relatively impermeable soil layer and the existence of a hydraulic gradient within a dispersible soil layer (Trzcinka *et al*, 1993). The most important of these is the periodic cracking of the soil which allows the entry of runoff, and the presence of dispersible subsoil. Water enters the soil via the cracks causing dispersion, the dispersed soil is then removed by seepage. Eventually the seepage path develops into a tunnel and the soil transported and deposited on the gully floor (Edwards *et al*, 1989).

Tunnel erosion occurs in duplex soils characteristically having a hard and resistant silty loam crust, a structureless and pale grey silty loam below, and a yellow, highly dispersive subsoil clay of low permeability (CSIRO, 1983; Leeper, 1967). Soils derived from granites appear to be less prone to tunnel erosion. Rock types most commonly associated with tunnel erosion are quartzites, slates, shales and schists (Newman and Phillips, 1957).

In areas of high rainfall the vegetation cover is dense and the interlocking roots aid the development of tunnels by holding the topsoil in place when the subsurface soil material is removed. Whereas, climates which are seasonally dry with sparse vegetation cover, surface cracking forms, causing uneven infiltration and accelerating tunnel development, with processes varying considerably between sites (Crouch *et al*, 1986).

Tunnels develop or extend when a wet period follows a period of drought. During a drought the subsoil is dry and cracks, the surface soil becomes hard and impervious with a decrease in vegetation cover. The runoff has increased due to the rain and uneven infiltration provides ideal conditions for the development of tunnel erosion. When the conditions continue to be wet, the soil becomes saturated and soil particles are being dispersed. Free water flows in the small tunnels that have already formed, being enlarged by dispersive action and abrasion of the sides and floor of the tunnels (Newman and Phillips, 1957). Tunnelling can also be caused by subsurface flowline convergence. Under natural conditions, flowline convergence is caused by surface or bedrock topography (Bryan and Yair, 1982).

2.2.4 Types of Tunnel Erosion

According to Crouch (1976), the three types of field tunnel erosion are:

1. shallow tunnels found in either the A2 horizon or the top metre of the B horizon (Figure 2.3);

2. deep tunnels located in the B horizon (Figure 2.4). Sometimes known as tunnel-gully erosion confined to steep slopes which initiate the development of gullies; and

3. deep tunnels initiated by gullies and contributing to the expansion of gullies (Figure 2.5 and Figure 2.6).

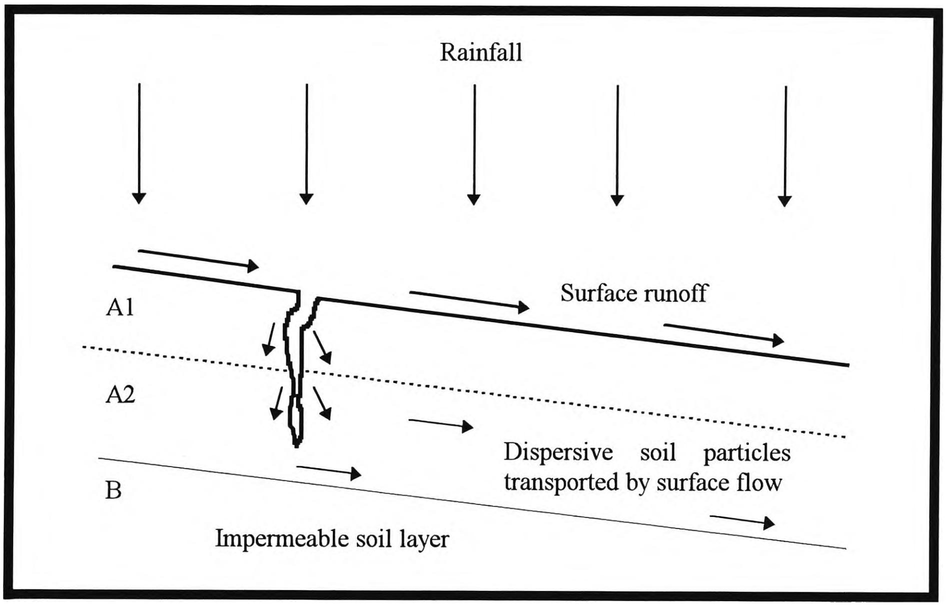

Figure 2.3: Shallow tunnels formed due to surface soil cracks, water infiltrating down the cracks entering the subsoil and dispersing. The dispersed soil particles are transported (laterally) by the water due to the hydraulic gradient, resulting in tunnels (modified from Crouch, 1976).

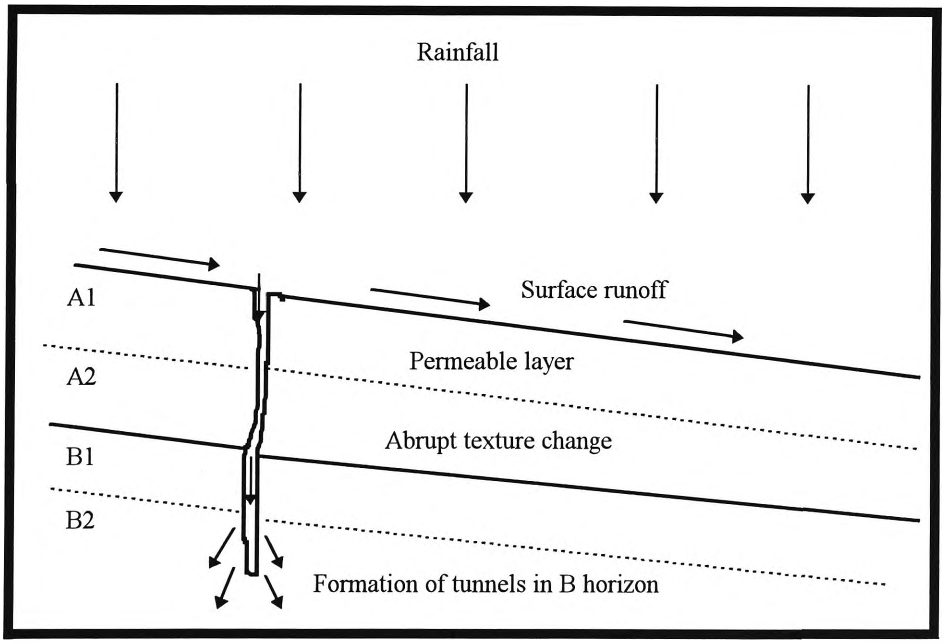

Figure 2.4: Deep tunnels formed in the deep B horizon initiate the development of gullies. Water infiltrates vertically through deep surface soil cracks eroding the dispersible soil located at the B horizon (modified from Crouch, 1976).

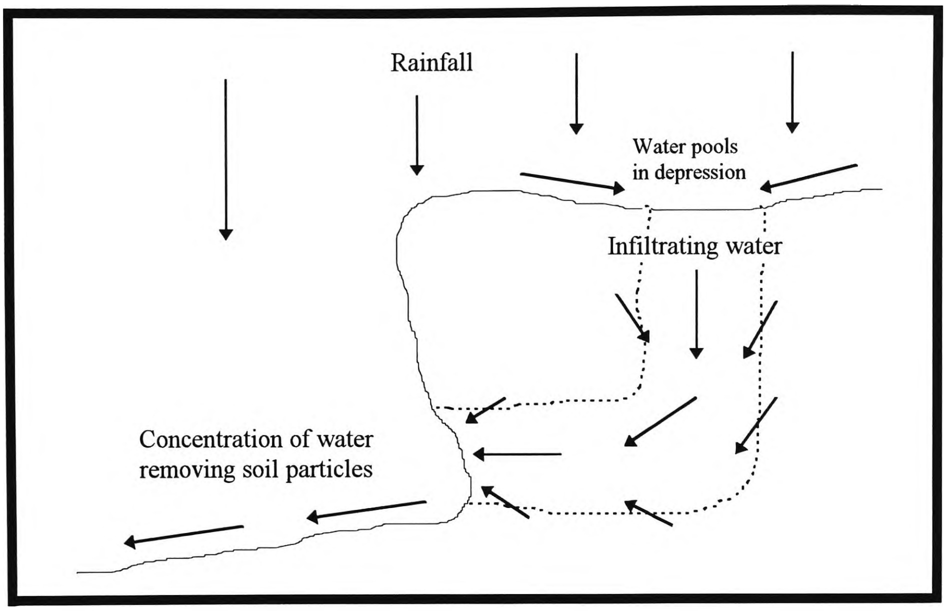

Figure 2.5: Tunnels initiated by gullies due to water concentrating at a point in the gully wall (modified from Crouch, 1976).

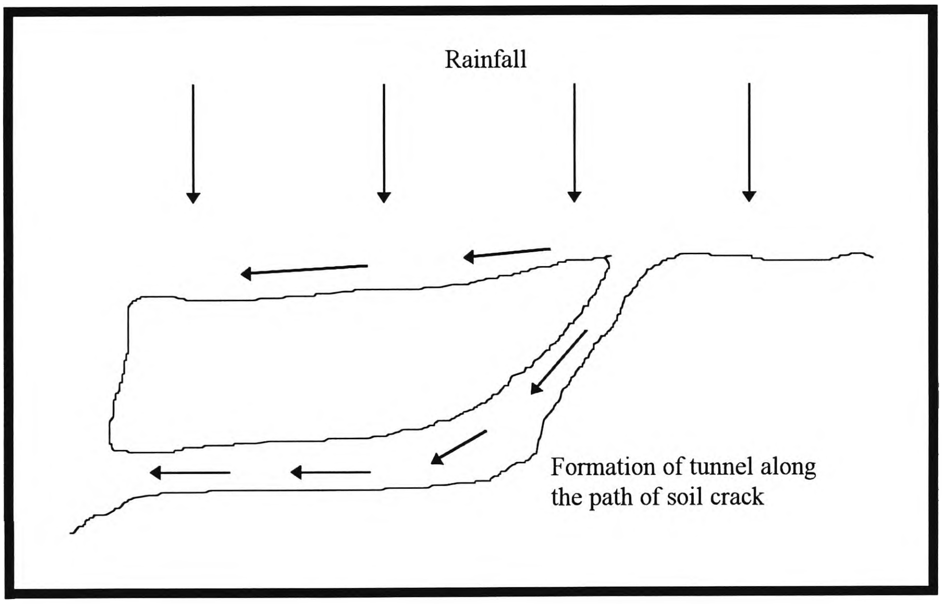

Figure 2.6: Tunnels initiated by gullies due to cracks in the side of the gully drying quickly (modified from Crouch, 1976).

2.2.5 Reclamation of Tunnel Eroded Areas

Vegetation cover reduces rapid drying out of the surface soil and reduces cracking, also helping control sheet, rill and gully erosion (Floyd, 1974). Perennial vegetation which penetrates deep into the clay and opposes movement of both soil and water is an effective control method for tunnelling. Woodland cover seems to have a distinct effect on reducing the incidence of tunnel erosion. Trees such as the Black Wattle (*Acacia mearnsii*), Yellow Gum (*Eucalyptus* sp.) and

Red Box (*Eucalyptus hemiphloia*) have all been successfully used to control tunnel erosion in Victoria where no alternative treatment has succeeded (Newman and Phillips, 1957).

The dispersibility of the soil can be decreased by reducing the forces applied to the particles, increasing the strength of the bonds between these particles. Decreasing the volume or the rate of flow of the ground water reduces the forces acting on the soil (Crouch, 1976). Increasing the strength of the bonds is achieved by replacing the exchangeable sodium ions by the addition of calcium (Sumner, 1993). The CSIRO (1983) also reported treating dispersive soils with gypsum or lime, otherwise tunnelling will continue.

An impermeable layer is also essential in the development of tunnels and accentuates the erosion problem. Deep ripping is conducted to break the impermeable layer in order to control shallow tunnelling. Ripping is only suitable where the impermeable layer is close to the surface so that the soil fractures and no deep tyne marks are left on the surface layer (Crouch, 1976). Inappropriate ripping can be unsuccessful and aggravate the problem even further. While contour ripping is found to break up existing tunnels, the effect is only temporary as new tunnels may develop due to the destruction of the A horizon (Floyd, 1974).

A common method of controlling tunnel erosion is a combination of the previous methods already stated. For example, shallow tunnelling in the Riverina District of NSW has been controlled by deep ripping, the establishment of pasture, the treatment of the soil with gypsum, and regular cultivation (Crouch, 1976).

2.3 SODIC SOILS

2.3.1 Defining Sodic Soils

A soils sodicity is generally expressed in terms of the ESP. In Australia, ‘non-sodic’ soils have an ESP value of less than 6, ‘sodic’ soils range from 6 to 14, and 15 or higher for ‘strongly sodic’ soils. An ESP exceeding 6 signifies clay dispersion, while a ESP greater than 12 indicates spontaneously dispersive clay soils (Sumner, 1993). Dispersion is also a function of other exchangeable cations (e.g., magnesium), salt concentration of the percolating water and clay minerals (Boucher, 1990).

Northcote and Skene (1972) reported that Australian soils having a value of ESP greater than 6 in the top 1 metre behaved differently than those in other parts of the world (Sumner, 1993).

Australian soils have been classified as having lower ESP values for sodic soils due to the lower contents of soluble minerals (e.g., calcium) which are necessary to maintain electrolyte concentration during leaching (Rengasamy and Olsson, 1991). The generally accepted definition of a sodic soil in Australia is one which has an ESP value exceeding 5, although clays with ESP less than 5 can disperse (McKenzie *et al*, 1993). ESP is calculated by Equation 2.1.

$$ESP = 100 \frac{\text{Exchangable } Na^{+}}{\text{Exchangable } (Ca^{2+} + Mg^{2+} + K^{+} + Na^{+} + Al^{3+})}$$

Equation 2.1: Exchangeable sodium percentage where the exchangeable bases and aluminium are expressed in $cmol.kg^{-1}$ (Chartres, 1993; Sumner, 1993).

An alternative measure of sodicity is the SAR of the soil solution given in Equation 2.2.

$$SAR = \frac{Na^{+}}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}}$$

Equation 2.2: Sodium Absorption Ratio in soil solution. The ion concentrations are expressed in $mmol.L^{-1}$ (Chartres, 1993; Sumner, 1993).

The SAR equation (Equation 2.2) is thermodynamically appropriate because it approximates to the activities of the various ions in solution (Chartres, 1993). The behaviour of sodicity is not only a function of ESP and SAR, but also the ionic composition of a soil solution at any given ESP and SAR value (Naidu *et al*, 1993). Rengasamy and Olsson (1991) proposed a classification system for sodic soils based on the SAR, threshold electrolyte concentration (TEC) and electrical conductivity (EC) for Australian soils (Figure 2.7). TEC is the electrolyte concentration at which dispersion occurs. TEC can be determined from the relationship with EC for solutions at which dispersion is observed to occur (Equation 2.3).

$$10 \times EC\,(dS.m^{-1}) \approx TEC\,(cmol.L^{-1})$$

Equation 2.3: The relationship between EC and TEC (Sumner, 1993).

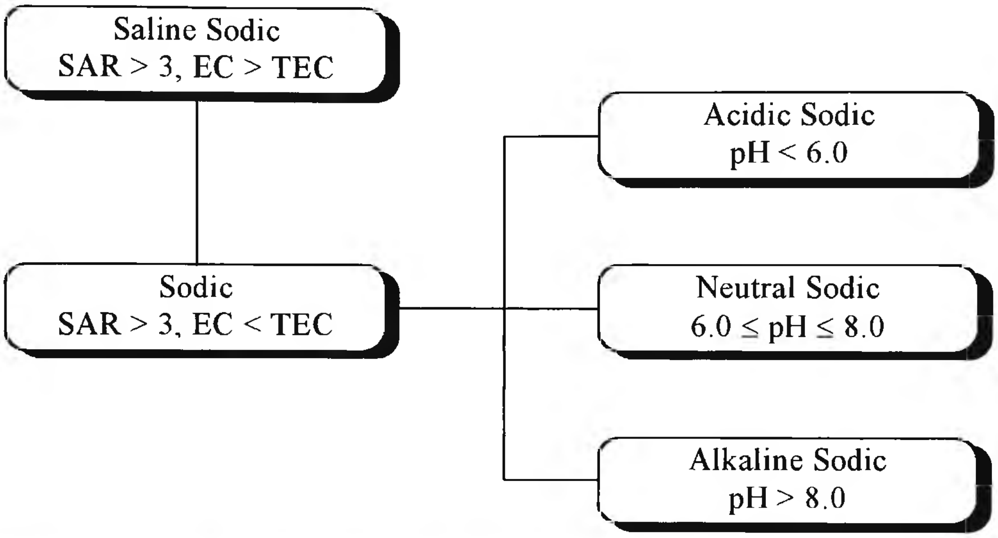

Figure 2.7: Classification of sodic soils due to SAR, EC, TEC and pH present in a 1:5 soil/water solution (modified from Rengasamy and Olsson, 1991).

2.3.2 Distribution of Sodic Soils

Northcote and Skene (1972) estimated that approximately 46.7 % of NSW soils are sodic (ESP ≥ 6). This data is an approximation based on a limited number of field observations. Areas where sodic soils are found include the Bathurst-Orange region, the Riverina and the Murray-Darling Basin. The majority of sodic soils occur in the subhumid regions of Australia and at lower elevations due to the accumulation of water, leaching products and evaporation (Chartres, 1993).

2.3.3 Formation of Sodic Soils

Sodic soils show limited pedological organisation and are often characterised by high concentrations of soluble salts. If the soluble salts are leached out of the soil, structural and morphological changes occur. This results in the development of a bleached, neutral to slightly alkaline, massive A2 horizon, with clay dispersion occurring in the B horizon. This eventually results in a highly sodic duplex soil. In Australia these soils are widespread, with sodic features occurring in both surface and subsurface horizons (Chartres, 1993; Naidu *et al*, 1993).

Properties which influence the formation and behaviour of sodic soils include weathering/leaching ratios, chemical composition and salinity of water interacting with the profile, mineralogy of the clay fraction, the presence or absence of certain cations, oxides and hydroxides (e.g., iron and aluminium) and soil texture (Chartres, 1993).

2.3.4 Clay Mineralogy

Exchangeable sodium leads to both swelling and/or dispersion of aluminosilicate minerals in the presence of water. Illites are more dispersive than montmorillonite in solutions of higher total cation concentration. In Australia, tunnelled soils are associated with illite and kaolinite, rather than montmorillonite (Fitzpatrick *et al*, 1995). Mineralogy directly influences both the effect of exchangeable sodium on hydraulic conductivity and the impact of other exchangeable ions on sodium (e.g., magnesium enhances the dispersion of illites when compared with calcium) (Churchman *et al*, 1995).

2.3.5 Exchangeable Cations

Emerson (1967) recognised the degree of dispersion of aggregates was dependent upon the ESP. It was found that soils with high levels of exchangeable sodium and magnesium had a high dispersion potential. Rengasamy (1983) found that illite would disperse at low ESP values when the exchange sites were occupied by magnesium rather than calcium.

It has been shown by Aylmore and Quirk (1962) that sodium saturated clay swells more than calcium-clay, with the swelling in the sodium-clay increasing rapidly as the solution electrolyte concentration decreases. Calcium carbonate acts as a cementing agent due to the concentration of calcium in the soil solution which limits dispersion. Swelling occurs to the extent that the clay particles become detached from each other and the clay spontaneously disperses (So and Aylmore, 1993).

Heede and de Bano (1984) showed that when enough sodium had been leached from the eroded soils, the soil became stable and easily vegetated. This study suggested that an intricate relationship existed between erosion, soil chemistry and gully bank stability.

2.3.6 The Influence of Organic Matter on Sodicity

In sodic soils, the accumulation of organic matter in aggregates is ineffective in stabilising their structure since organic linkages involving sodium ions are weak. Sodium-organic complexes are highly soluble and mobile, and the degree of covalent bonding between organic molecules and sodium is very low due to its low ionic potential (Naidu and Rengasamy, 1995). The sodium needs to be replaced by multivalent cations which aids the formation of stable linkages between particles by organic matter (Rengasamy and Olsson, 1991).

2.3.7 Reclamation of Sodic Soils

Sumner (1993) suggested that the reclamation of a sodic soil by chemical amelioration consists of reducing or removing the exchangeable sodium, and increasing the electrolyte concentration of the soil solution. This process involves the addition of ions such as calcium to replace the sodium. To maintain a sufficient electrolyte concentration is important, as this determines the rate of water intake on which reclamation depends. These two requirements can be achieved by the application of gypsum, which is economically viable. Unless the soil solution concentration is maintained at a high enough level to prevent swelling and dispersion, physical degradation will result.

3 METHODS

3.1 SAMPLING SITES

Three study sites were identified in the Bungonia District situated on the properties of *Inverary Park* and *Inverary*. Bungonia 1, known as *Winston Gully*; Bungonia 2 and Bungonia 3 form part of Limekiln creek approximately 34° 53' 00" S latitude and 149° 58' 30" E longitude (Figure 3.1). These sites were selected because of the different contemporary processes and soil types (physical and chemical properties) occurring within a kilometre of each other. Description and sampling of soils, some measurements, and the identification of the soil physical processes were performed at the three sites. Samples were collected for further physical and chemical analysis in the laboratory.

Winston Gully was situated on the property of *Inverary Park* at the head of Limekiln Creek (GR 716352) (Plate 3.1). The vegetation surrounding the gully consists primarily of native grasses with little ground cover present. A few species of Acacia are established within the gully, and some species of Eucalypts and *Pinus radiata* (planted by the local Landcare group) surround the outskirts of the gully and the two properties.

The second sampling site (Bungonia 2) was located on the western section of Limekiln Creek, Grid Reference 711356. This area consists of two different soil types, that is, a Holocene Black Clay overlaying an Quaternary Orange Sand (Plate 3.2), and a sodic soil undergoing contemporary erosion (Plate 3.3). The third sampling site (Bungonia 3) was situated parallel to *Winston Gully* forming part of a minor channel off Limekiln Creek (GR 718349) (Plate 3.4).

A morphological profile description for each of the three sites is outlined in Appendix A.1 to A.3. A determination of field soil texture at the sites was not conducted because the vertical exposures have been exposed over a long time period becoming altered by seasonal changes of the environment as cited in McDonald *et al* (1990).

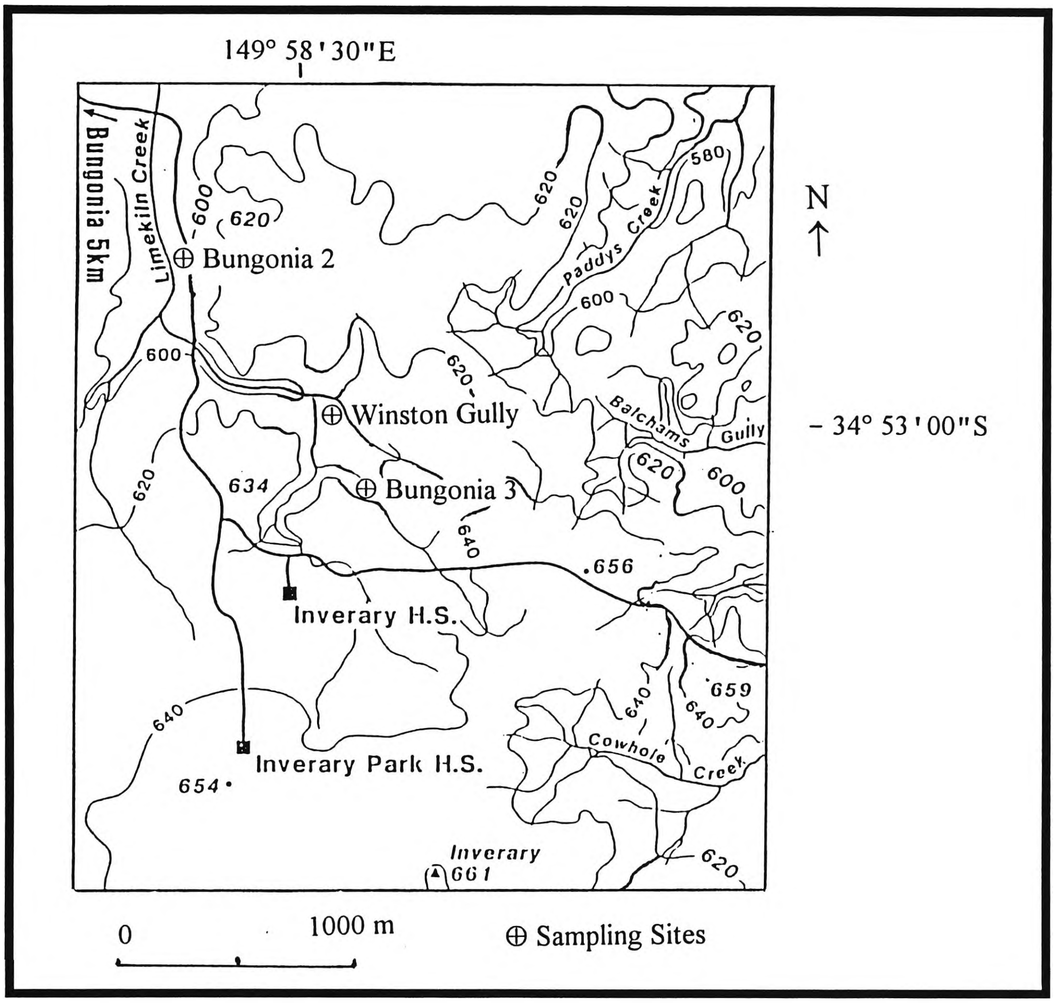

Figure 3.1: Location map of the three sampling sites at Bungonia (Kooringaroo 8828-11-S 1:25000).

Plate 3.1: *Winston Gully* site located at the head of the gully (east) looking west.

Plate 3.2: Bungonia 2 sampling site consisting of Holocene Black Clay and Quaternary Orange Sands.

Plate 3.3: Bungonia 2 sampling site 50 m north of the Holocene Black Clay and Quaternary Orange Sands.

Plate 3.4: Bungonia 3 sampling site, approximately 750 m south of *Winston Gully*.

3.2 FIELD TECHNIQUES

3.2.1 Shear Strength Testing

A H-60 Field Inspection Vane Tester was used in the field to test the shear strength of the clays present down a profile at *Winston Gully* (Appendix A.7). The shear strength of the clays at Bungonia 2 and 3 could not be tested due to the extreme dryness of the soil during the study period. The field inspection vane tester allowed quick and easy determination of the undrained shear strength of clays present within the gully. It was possible to measure shear strength of 0–20, 0–10 and 0–5 $t.m^{-2}$ depending on the size of the vane used. The accuracy of the vane tester is within 10% of the reading (Geonor A/S Instruction Manual).

3.2.2 Surveying

Gully cross-sections were surveyed randomly across the edge of the arms of *Winston Gully* (Figure 3.2). From these cross-sections the area of material removed by downcutting and sidewall retreat was determined using the following method and equations obtained from Veness (1980).

$$\text{Downcutting Area} = \text{Channel Width} \times \text{Gully Depth}$$

Equation 3.1: Downcutting area calculation.

$$\text{Sidewall Retreat Area} = \text{Total Area} - \text{Downcutting Area}$$

Equation 3.2: Sidewall retreat calculation.

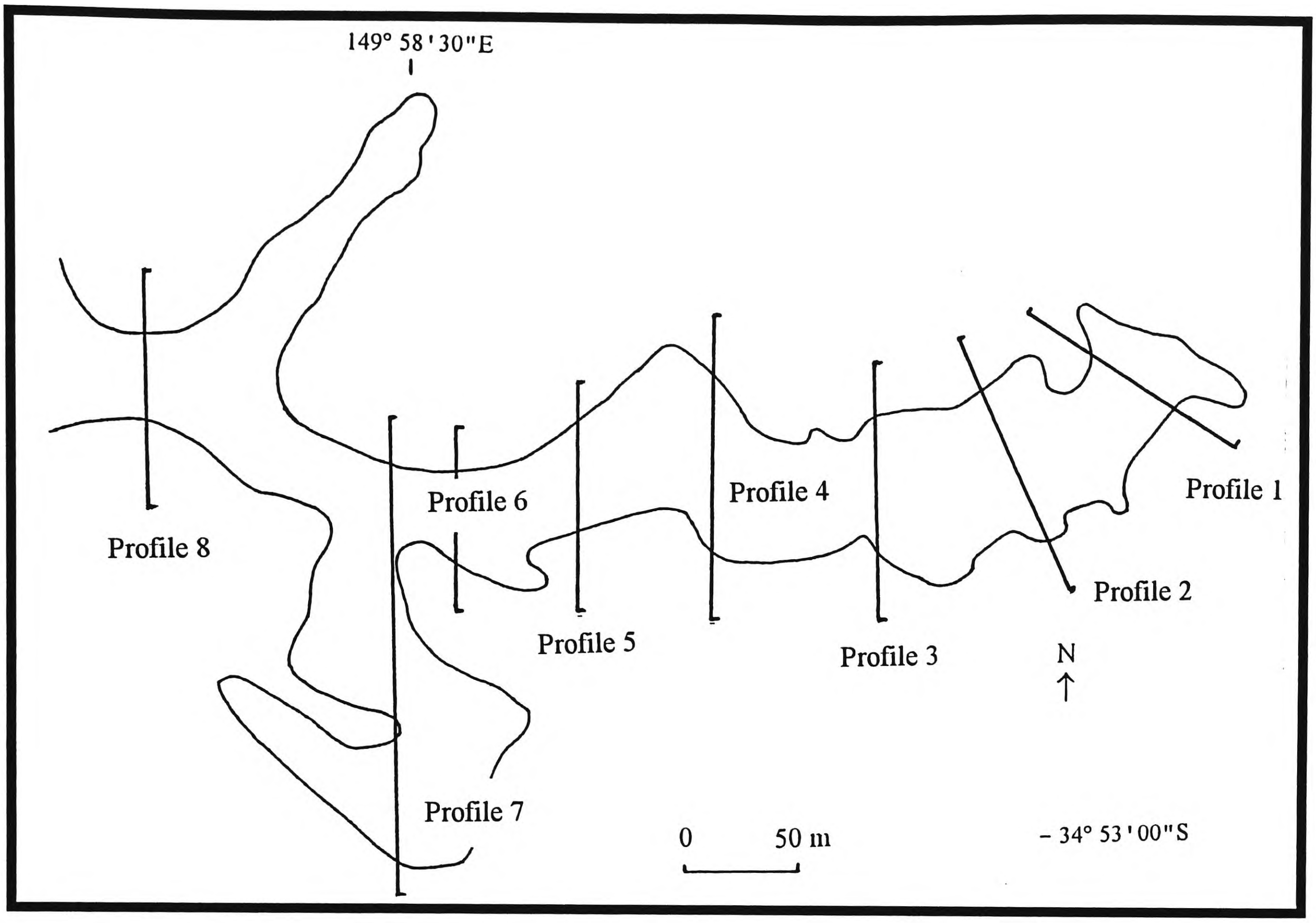

Figure 3.2: Location of the profiles conducted at *Winston Gully*.

3.3 LABORATORY TECHNIQUES

3.3.1 Soil Sample Preparation

Soil samples were collected from individual areas and horizons at each of the three sites. The soil samples where brought back to the laboratory for both physical and chemical analysis. Apart from samples used for determination of bulk density, the soil was broken down into smaller clods, with the root material and large stones removed. The samples were then allowed to air dry for approximately four to six weeks. The materials were fractionated by coning and quartering, and halved. The air-dried materials were worked through a 2000 μm sieve and larger aggregates removed and crushed by mortar and pestle. The samples were then thoroughly mixed by the method of coning and quartering which allows a homogenous representative sample to be acquired for further analysis. The remaining bulk material was stored in glass jars.

3.3.2 Determination of the Soil Moisture Content and Moisture Factor

Soil samples collected for moisture content were sealed in air tight bags (to prevent moisture loss) and analysed within 24 hours to minimise errors. The moisture content was determined by firstly weighing a sample of field moist soil, then re-weighing the sample after drying in an oven at 105°C to remove all the moisture (Equation 3.3).

$$\text{Soil moisture content \%} = 100\ \frac{\text{weight of moist soil} - \text{weight of oven dry soil}}{\text{weight of oven dry soil}}$$

Equation 3.3: Soil moisture content.

The moisture factor represents the difference in weight between air dry and oven dry soil samples, and is required to convert the results of the chemical analysis from an air dry to oven dry basis. The moisture factor was determined by weighing a sample of soil that had been left to air dry. The sample was then placed in an oven to remove any remaining moisture and re-weighed (Equation 3.4).

$$\text{Moisture Factor} = \frac{\text{air dry weight of soil}}{\text{oven dry weight of soil}}$$

Equation 3.4: Moisture factor (MF).

3.3.3 Bulk Density and Porosity

Large clods were collected from the three sites and air-dried for up to 2 weeks. No significant decrease in volume was noted on drying. Three samples from each horizon were coated in wax, weighed in air and then re-weighed in a beaker containing water (to determine the displaced volume). The bulk density was calculated by air mass/displaced volume multiplied by the moisture factor. Assuming a particle density of 2.65 $g.cm^{-3}$, the total porosity of a sample was calculated using Equation 3.5.

$$\text{Porosity \%} = 100\left(1 - \frac{\text{Bulk density}}{\text{Particle density}}\right)$$

Equation 3.5: Porosity.

3.3.4 Particle Size Analysis

Particle size analysis (PSA) was performed to determine the size distribution of the particles of each soil sample. The hydrometer method allows for non-destructive sampling of suspensions undergoing settling. This provides multiple measurements on the same suspension so that detailed particle size distributions can be obtained with minimum effort (Gee and Bauder, 1986).

PSA analysis was conducted on field moist soil samples using the hydrometer method adapted from the New Zealand Standard Specification 4402 Method SP 6.1 (Thomas, 1981). This method covers the measurement of particle size distribution of soil material finer than 2000 μm. An error of ±1 $g.L^{-1}$ hydrometer reading results in an error of ±2 weight % for clay-size particles (Gee and Bauder, 1986).

3.3.5 Water-Stability of Soil Aggregates

The water-stability of soil aggregates measures the extent of soil particles likely to remain intact and separate under the influence of water and mechanical disturbance. The stability of soil aggregates was determined using the wet-sieving method. Soil samples were air-dried for a few weeks with the roots and plant material removed. Approximately 50 g of air dry soil was passed through the stacked sieves (2000 μm, 600 μm and 63 μm) and immersed in water using a high pressure hose to mechanically disturb the soil particles. The aggregates remaining on each sieve were transferred to moisture cans, oven-dried at 105°C and weighed. The primary soil particles amongst the aggregates remaining were determined by crushing and dispersing with a high pressure hose through each of the three sieves. Due to dispersion by water, coarse sand and gravel remained on the sieves after the second sieving. The primary particles were removed from each sieve, oven-dried and re-weighed.

The content of water stabile aggregates are given by the following equations.

$$C_1 = 100\left(\frac{W_{A1} - P_1}{T_w - P_1}\right)$$

Equation 3.6: Water stable aggregates greater than 2000 μm.

$$C_2 = 100\left(\frac{(W_{A1} + W_{A2}) - (P_1 + P_2)}{T_w - (P_1 + P_2)}\right)$$

Equation 3.7: Water stable aggregates greater than 600 μm.

$$C_3 = 100\left(\frac{(W_{A1} + W_{A2} + W_{A3}) - (P_1 + P_2 + P_3)}{T_w - (P_1 + P_2 + P_3)}\right)$$

Equation 3.8: Water stable aggregates greater than 63 μm.

T_W is the total weight of soil; W_{A1} is the weight of aggregates retained on the top (2000 μm) sieve; P_1 is the weight of primary particles retained on the top (2000 μm) sieve; W_{A2} is the weight of aggregates retained on the middle (600 μm) sieve; P_2 is the weight of primary particles retained on the middle (600 μm) sieve; W_{A3} is the weight of aggregates retained on the bottom (63 μm) sieve; and P_3 is the weight of primary particles retained on the bottom (63 μm) sieve.

3.3.6 X-Ray Diffraction

X-ray diffraction for the identification of minerals and clay type was conducted on soil samples from the three sites. The method used by the University of Wollongong is described in detail in Hutchinson (modified 1974). X-ray diffraction was carried out using a Philips PW 1150 diffractometre using Copper Broad Focus X-ray tube at 40 keV and 30 mÅ. The clays were extracted on porous ceramic plates by vacuum filtration (standard method) and bulk sampling was conducted to determine the mineralogy of the soils. X-ray diffraction using glycerol solvation, heating (500°C) and normal samples was then carried out on each clay sample. Diffractograms were made with $Cu_{K\alpha}$ radiation over the range 2–20° of 2θ. The mineralogy was identified using 'Traces'™ software and the clay diffraction patterns were reported in terms of interplanar spacing (*d* spacings). The clay mineralogy was determined by comparing the diffractograms with standard clay diffractograms.

3.3.7 General Chemical Tests

Soil samples were firstly tested qualitatively for the presence and absence of calcium carbonate, soluble carbonates, soluble sulphates, soluble chlorides and organic matter (Appendix A.8 to A.10). Each sample was mixed with distilled water and filtered, with the filtrate tested for the above parameters (Charman and Murphy, 1991).

3.3.8 Determination of Total Organic-Carbon by the Walkley-Black Method (Blakemore *et al*, 1987)

Air-dried soil samples were sieved through a 250 μm sieve. The organic matter present in the soils was oxidised by using potassium dichromate ($K_2Cr_2O_7$) with the reaction being facilitated by the addition of concentrated sulphuric acid (H_2SO_4 98%). The $K_2Cr_2O_7$ not used totally in oxidation was determined by titration using standard ferrous ammonium sulphate. Duplicates were conducted for each sample to determine a mean titration. The amount of organic carbon oxidised was calculated from the volume of dichromate reduced expressed as a percentage of the dry weight of the soil used in the experiment.

3.3.9 Determination of Exchangeable Hydrogen (H^+) and Aluminium (Al^{3+}) (Yuan, 1959)

An air-dried, 2000 μm sample (10 g) of soil was weighed accurately, placed in a conical flask, equilibrated with 50 mL potassium chloride (KCl, 1 $mol.L^{-1}$) and allowed to stand for approximately 1 hour, and the pH measured. The sample was then filtered, the extract which contains H^+ and Al^{3+} collected. Phenolphthalein (0.1%) indicator was added to the extract and titrated with sodium hydroxide (NaOH, 0.1 $mol.L^{-1}$) to the end point. A few drops of hydrochloric acid (HCl, 0.1 $mol.L^{-1}$) solution was then added to remove the pink colouration followed by 10 mL of sodium fluoride (NaF, 4%) to observe if the soil extract contained extractable Al^{3+} (the presence of the pink colour returning). When the pink colour returned, the extract was titrated with HCl until the colour just disappeared. The titration data, exchangeable H^+ and Al^{3+} in the original soil samples were calculated using Equation 3.9. Duplicate tests were conducted for each sample to determine a mean titration. NaOH was standardised with potassium hydrogen phthalate ($KHC_8H_4O_4$), and HCl with the NaOH solution. Due to the unbuffered solutions, the extractions are at or near the pH of the soil.

$$\begin{aligned} H^+ + Al^{3+} &= 10 \times \text{volume NaOH} \times \text{concentration NaOH} \times \text{MF} \\ Al^{3+} &= 10 \times \text{volume HCl} \times \text{concentration HCl} \times \text{MF} \\ H^+ &= \left(H^+ + Al^{3+}\right) - Al^{3+} \end{aligned}$$

Equation 3.9: Determination of exchangeable hydrogen and aluminium.

3.3.10 Determination of Exchangeable Bases, Total Exchangeable Bases, Cation Exchange Capacity, Exchangeable Sodium Percentage and Base Saturation (Blakemore *et al*, 1987)

In order to determine the sodicity (exchangeable sodium percentage) of soils, the total exchangeable bases and cation exchange capacity need to analysed. Extraction of cations from the soil samples was conducted using the ammonium acetate (NH_4OAc, 1 $mol.L^{-1}$, pH 7) method of shaking and centrifuging. Approximately 10 g of air-dried soil (< 2000 μm) was placed in a centrifuge tube and shaken for 30 minutes with 25 mL of NH_4OAc. The samples were then placed in a centrifuge for 15 minutes and the supernatant decanted. This method of cation extraction was conducted three times for each sample. Some of the supernatant contained large amounts of organic material which was then filtered.

Atomic absorption standards for Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} were prepared to calibrate the Atomic Absorption Spectrometer (AAS). The supernatants were diluted where necessary and analysed for the concentration of cations ($mg.L^{-1}$) displaced from the soil.

The concentrations (X) of exchangeable bases (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}), the TEB, ESP, and BS were determined from the following equations.

$$X = \frac{100 \times C \times D \times V \times MF}{1000 \times E \times W}$$

Equation 3.10: Concentration of individual exchangeable bases ($cmol.kg^{-1}$).

Where C is the concentration ($mg.L^{-1}$) from AAS results (Appendix A.4 to A.6); D is the dilution factor; V is the initial volume of supernatant (mL); MF is the moisture factor; E is the equivalent weight ($Ca^{2+} \approx 20.0$, $Mg^{2+} \approx 12.16$, $Na^{+} \approx 23.0$, and $K^{+} \approx 39.0$); and W is the weight of soil (10 g).

$$TEB = Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}$$

Equation 3.11: Determination of Total Exchangeable Bases ($cmol.kg^{-1}$).

$$CEC = TEB + \text{Exchangeable acidity } (H^{+} + Al^{3+})$$

Equation 3.12: Cation Exchange Capacity ($cmol.kg^{-1}$).

$$ESP\,(\%) = 100\,\frac{\text{Exchangeable } Na^{+}}{CEC}$$

Equation 3.13: Exchangeable Sodium Percentage.

$$BS(\%) = 100\ \frac{TEB}{CEC}$$

Equation 3.14: Base Saturation.

The base saturation percentage is the portion of soil CEC accounted for by exchangeable bases, which can be used to determine soil fertility.

3.3.11 pH

This method is a direct measurement of pH based on a soil/solution ratio of 1:5 for 1 hour at room temperature. The pH of the soil extract was measured using a pre-calibrated glass electrode system.

3.3.12 Electrical Conductivity

The electrical conductivity of soil suspension was measured using a Philips PW9501 conductivity metre whose precision is between 0.1 and 1.0% (according to operating manual). The method is based on a 1:5 soil/water extract at 25°C (automatically corrected) on air dry basis as described in Rayment and Higginson (1992).

4 RESULTS

4.1 INTRODUCTION

A preliminary examination was conducted at *Winston Gully*, Bungonia 2 and Bungonia 3 in order to identify the contemporary erosive processes occurring at each site. Once the erosive processes of each site were identified, sampling points were selected for field measurements and laboratory analysis of the soils. The results obtained are presented in this chapter and the relationship between the physical and chemical characteristics to the processes at each site will be further discussed in chapter 5.

4.2 PHYSICAL AND CHEMICAL ANALYSIS OF THE SOIL SAMPLES

4.2.1 Physical Analysis of Soils

The results of the physical analysis conducted on soil samples from the three study sites are given in Table 4.1 to Table 4.3, from which particle size distribution curves were produced (see Figure 4.1 to Figure 4.4). In summary, the following observations can be made of the physical characteristics of the soils.

- *Winston Gully* and Bungonia 2 contained high percentages of clay (mean of 41% and 55% respectively) within the B horizons.

- Bungonia 3 soils contained the highest composition of fine sand (> 63 μm), with 72% for the A horizons and 51% for the B horizons.

- Soil aggregates less than 63 μm from each site were found to be unstable in the presence of water, with those from the B horizons having a higher aggregate instability (96–84%) than those from the A horizons (47–77%).

- Aggregates of coarser material (2000–600 μm and 600–63 μm) in both the A and B horizons for all sites were found to be more stable in the presence of water.

- Bulk density values were generally high (1.29–2.03 $g.cm^{-3}$) resulting in porosity values usually less than 50%.

Table 4.1: Physical analysis of the soils at *Winston Gully* (N/A indicates data not available).

Sample	Horizon	Soil Moisture Factor	Sample Depth (m)	Particle Size Analysis (%)					Stability of Soil Aggregates (%)				Bulk Density ($g.cm^{-3}$)	Porosity (%)
				Sand			Silt	Clay						
				> 2000 µm	> 600 µm	> 63 µm	63 - 2 µm	< 2 µm	> 2000 µm	2000 - 600 µm	600 - 63 µm	< 63 µm		
1	A	1.00	0.1	3	5	40	33	19	0	12	11	77	1.41	47
	B	1.00	0.8	1	5	25	27	42	0	0	0	100	1.81	32
	C	1.00	5.0	N/A	N/A	N/A	N/A	N/A	0	1	3	96	N/A	N/A
2	A	1.01	0.1	0	1	31	51	17	0	14	12	74	1.50	43
	B	1.00	5.5	9	3	16	31	41	0	1	0	99	2.03	23
3	A	1.00	0.1	0	4	21	35	40	0	8	9	83	1.42	46
	B	1.00	6.0	0	1	26	30	43	0	1	1	98	1.68	36
4	A	1.00	0.1	2	7	22	26	43	0	11	23	66	1.64	38
	B	1.01	9.0	1	4	49	17	29	0	0	1	99	1.83	31
5	A	1.00	0.1	7	13	27	23	30	0	9	13	78	1.71	36
	B	1.02	1.7	11	20	15	3	51	0	1	3	97	1.74	34
6	A	1.00	0.1	2	6	51	36	5	0	15	30	55	1.53	42
	B	1.01	3.0	N/A	N/A	N/A	N/A	N/A	0	6	10	84	N/A	N/A

Table 4.2: Physical analysis of the soils at Bungonia 2 (N/A indicates data not available).

Sample	Horizon	Soil Moisture Factor	Sample Depth (m)	Particle Size Analysis (%)					Stability of Soil Aggregates (%)				Bulk Density ($g.cm^{-3}$)	Porosity (%)
				Sand			Silt	Clay						
				> 2000 µm	> 600 µm	> 63 µm	63 - 2 µm	< 2 µm	> 2000 µm	2000 - 600 µm	600 - 63 µm	< 63 µm		
1	B	1.01	0.4	0	2	12	33	53	0	4	2	94	1.87	29
2	B	1.00	1.0	1	1	4	16	78	0	0	1	99	1.89	29
3	B	1.02	1.5	5	11	39	10	35	0	7	19	74	N/A	N/A
4	B	1.03	4.0	N/A	N/A	N/A	N/A	N/A	0	18	21	61	N/A	N/A
5	A	1.19	1.0	N/A	N/A	N/A	N/A	N/A	0	13	40	47	1.55	42
	B	1.00	2.5	N/A	N/A	N/A	N/A	N/A	0	6	16	78	1.70	36
6	B	1.12	3.0	N/A	N/A	N/A	N/A	N/A	0	2	1	97	N/A	N/A

Table 4.3: Physical analysis of the soils at Bungonia 3 (N/A indicates data not available).

Sample	Horizon	Soil Moisture Factor	Sample Depth (m)	Particle Size Analysis (%)					Stability of Soil Aggregates (%)				Bulk Density ($g.cm^{-3}$)	Porosity (%)
				Sand			Silt	Clay						
				> 2000 µm	> 600 µm	> 63 µm	63 - 2 µm	< 2 µm	> 2000 µm	2000 - 600 µm	600 - 63 µm	< 63 µm		
1	A	1.00	0.4	N/A	N/A	N/A	N/A	N/A	0	10	32	58	N/A	N/A
	B	1.00	1.7	N/A	N/A	N/A	N/A	N/A	0	1	7	92	N/A	N/A
2	A	1.10	0.2	3	4	65	28	0	0	1	3	96	1.29	51
	B	1.00	1.1	0	1	50	10	39	0	1	4	95	1.88	29
	C	1.18	2.5	0	0	40	50	10	0	0	1	99	1.65	38

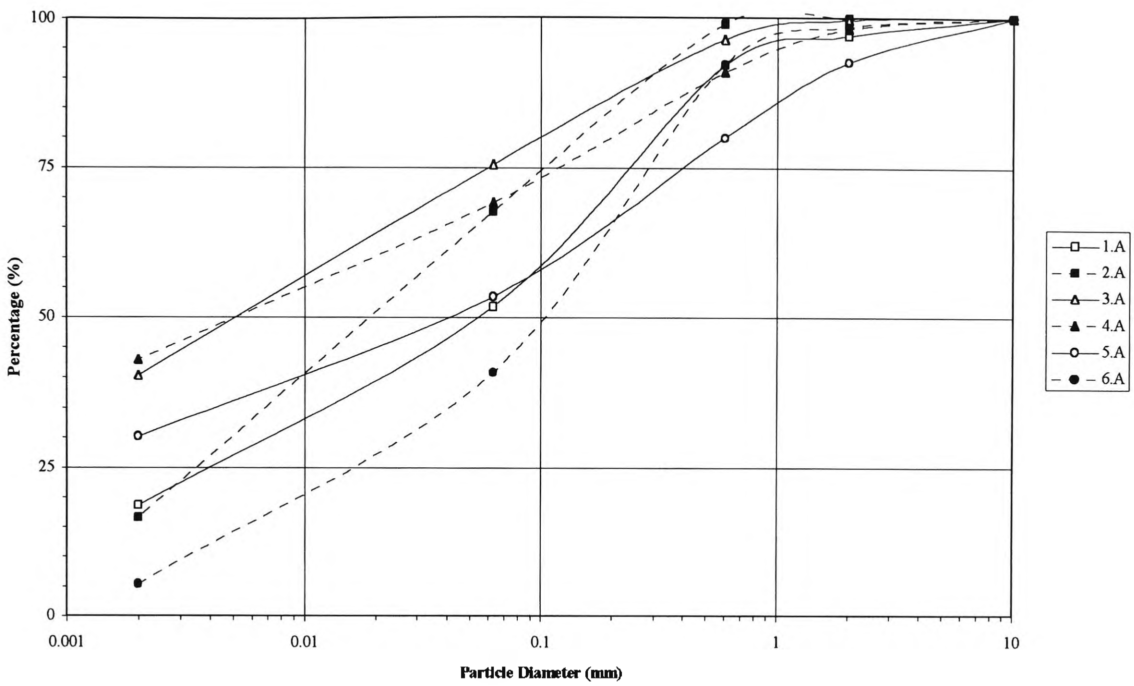

Figure 4.1: Particle size distribution curve for *Winston Gully* A horizons.

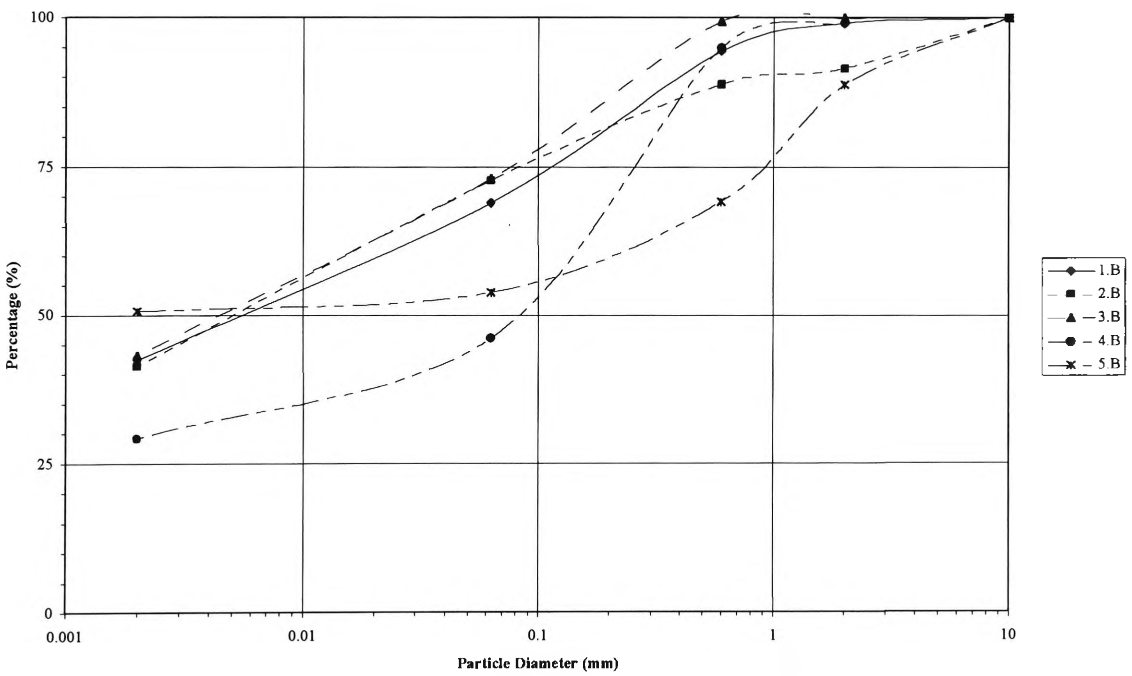

Figure 4.2: Particle size distribution curve for *Winston Gully* B horizons.

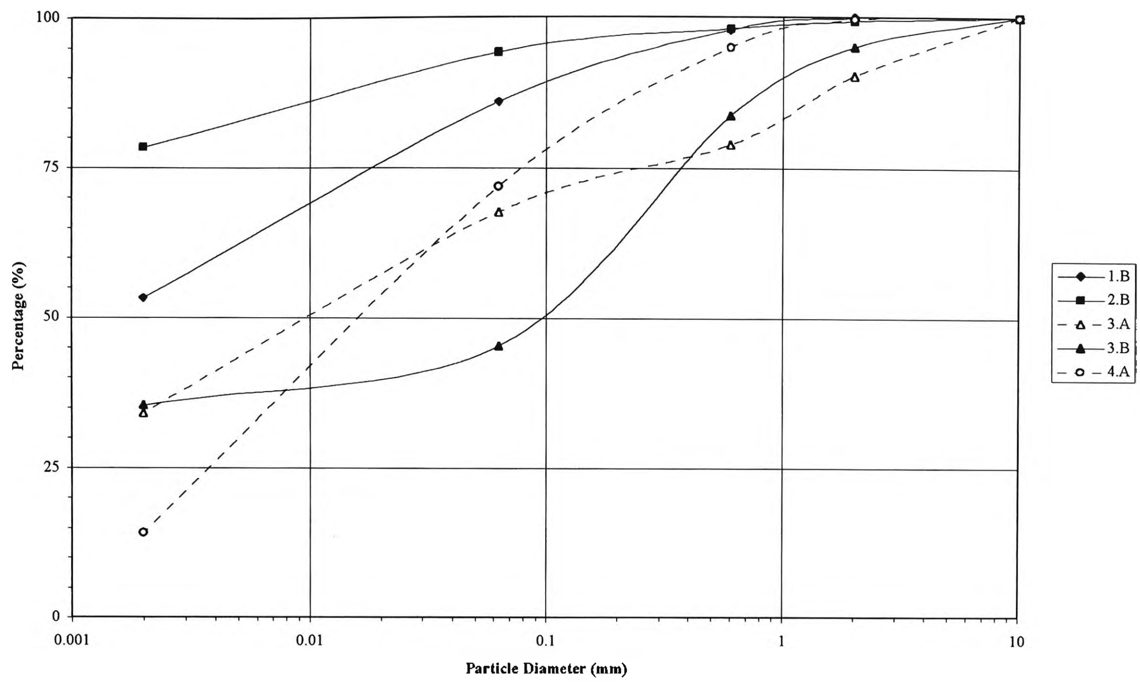

Figure 4.3: Particle size distribution curve for Bungonia 2.

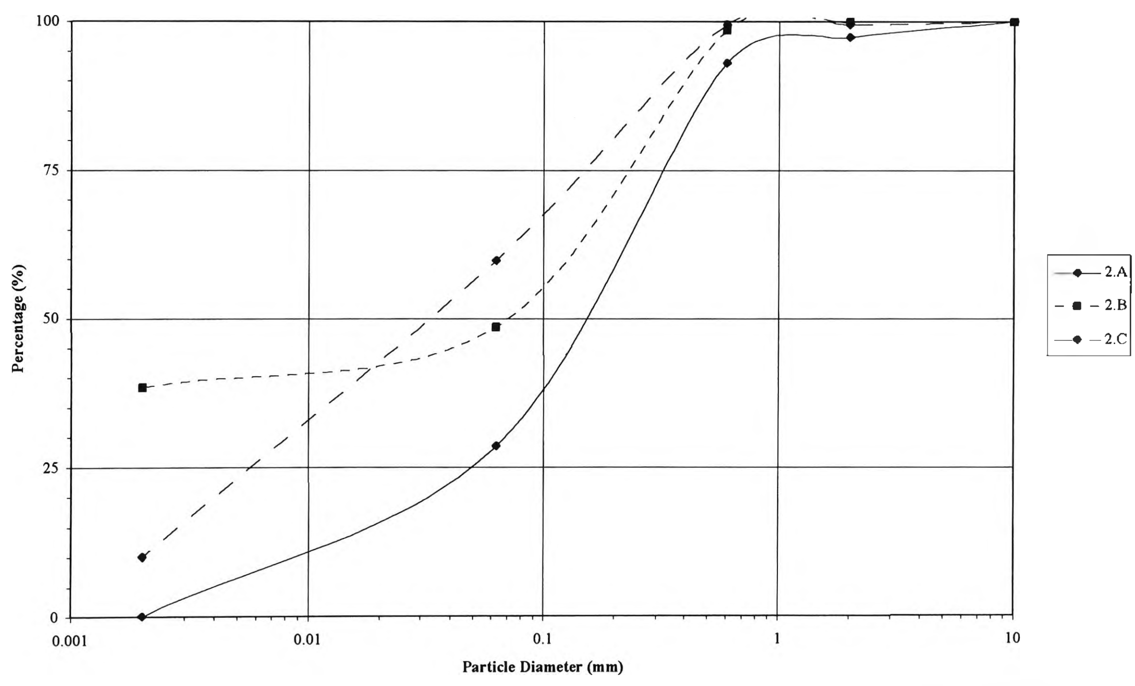

Figure 4.4: Particle size distribution curve for Bungonia 3.

Clay mineralogy results are illustrated in Table 4.4 to Table 4.6. The *Winston Gully* material is composed mainly of kaolinite, illite, quartz and muscovite, with montmorillonite located in the B horizon of the slump (sample 5) and stable hill (sample 6). Bungonia 2 and 3 samples exhibit similar mineralogy to *Winston Gully*.

Table 4.4: Mineralogy and clay type identified at *Winston Gully*.

Sample	Horizon	Description
1	A	Quartz, Muscovite, Kaolinite and Illite
	B	Quartz, Muscovite, Kaolinite and Illite
	C	Quartz, Muscovite, Kaolinite and Illite
2	A	Quartz, Muscovite, Kaolinite and Illite
	B	Quartz, Muscovite, Kaolinite and Illite
3	A	Quartz, Muscovite, Kaolinite and Illite
	B	Quartz, Muscovite, Kaolinite and Illite
4	A	Quartz
	B	Quartz, Muscovite, Kaolinite and Illite
5	A	Quartz
	B	Quartz, Muscovite, Kaolinite, Illite and Montmorillonite
6	A	Quartz and Kaolinite
	B	Quartz, Muscovite, Kaolinite, Illite and Montmorillonite

Table 4.5: Mineralogy and clay type identified at Bungonia 2.

Sample	Horizon	Description
1	B	Quartz, Muscovite, Kaolinite and Illite
2	B	Quartz, Muscovite, Kaolinite and Illite
3	B	Quartz, Muscovite, Kaolinite, Illite and Montmorillonite
4	B	Quartz and Kaolinite
5	A	Quartz, Muscovite, Kaolinite, Illite and Montmorillonite
	B	Quartz and Kaolinite
6	B	Quartz, Muscovite, Kaolinite and Illite

Table 4.6: Mineralogy and clay type identified at Bungonia 3.

Sample	Horizon	Description
1	A	Calcium aluminium silicate hydrate/Gismondine and Kaolinite
	B	Calcium aluminium silicate hydrate/Gismondine, Kaolinite, Illite, Montmorillonite and Muscovite
2	A	Quartz
	B	Quartz and Kaolinite
	C	Quartz, Muscovite, Kaolinite and Illite

4.2.2 Chemical Analysis of Soils

Table 4.7 to Table 4.9 present the results of the chemical analyses conducted on soil samples from the three study sites, and are discussed further in chapter 5. In summary, the following observations can be made of the chemical characteristics of the soils.

- At each site, the concentration of exchangeable sodium (mean = 2.01 $cmol.kg^{-1}$) and magnesium (mean = 7.70 $cmol.kg^{-1}$) was high, and increased down each soil profile. The calculated ESP values of 0–7% for the A horizons and 15–47% for the B and C horizons are considered high.

- The low concentrations of exchangeable calcium (mean = 3.00 $cmol.kg^{-1}$) and potassium (mean = 0.18 $cmol.kg^{-1}$) combined with a high ESP, has resulted in highly dispersive sodic soils.

- Exchangeable aluminium was only found at *Winston Gully* which is possibly related to the low pH values. The EAP of 16% is considered to be non-toxic and insignificant in the erosion present at this site.

- Each of the sites were found to have low concentrations of organic carbon (< 2%). The lack of organic binding and cementing agents (such as calcium) probably contributes to the instability of the soil aggregates (illite and kaolinite).

- Electrical conductivity decreased down each profile at the three sites, ranging from 0.000–0.210 $dS.m^{-1}$. The low electrical conductivity readings resulted in extremely low values (approximately zero) for the empirical determination of ionic strength of the soil solution. This further supports the observation that the soils are highly dispersive.

- The pH values of the soil solution were constant down a profile and between sites, with the mean pH level for each site ranging between 4.5 to 5.3.

Table 4.7: Chemical analysis of the soils at *Winston Gully*. EAP is the exchangeable aluminium percentage.

		Exchange Complex Data ($cmol.kg^{-1}$)								%				pH	Electrical Conductivity
Sample	Horizon	Ca^{2+}	K^{+}	Na^{+}	Mg^{2+}	Al^{3+}	H^{+}	TEB	CEC	ESP	EAP	BS	Organic Carbon	1:5 soil/solution ratio	($dS.m^{-1}$)
1	A	0.48	0.16	0.07	1.22	0.66	1.46	1.93	4.05	2	16	48	1.61	4.0	0.060
	B	0.04	0.08	6.58	6.04	0.00	2.39	12.75	15.13	44	0	84	0.63	4.2	0.080
	C	0.16	0.05	0.53	2.74	0.00	3.02	3.48	6.49	8	0	54	0.78	4.2	0.075
2	A	1.81	0.26	0.52	4.19	0.00	3.68	6.78	10.46	5	0	65	2.79	4.5	0.155
	B	0.14	0.18	3.82	3.05	0.57	0.33	7.19	8.09	47	7	89	0.61	3.9	0.008
3	A	0.53	0.14	0.81	4.30	0.81	4.55	5.78	11.14	7	7	52	1.41	3.8	0.180
	B	0.47	0.10	7.60	6.52	0.00	3.02	14.69	17.70	43	0	83	0.38	4.8	0.017
4	A	2.11	0.27	0.34	4.95	0.25	2.45	7.66	10.36	3	2	74	1.64	4.3	0.155
	B	1.33	0.07	5.62	7.61	0.00	3.45	14.63	18.09	31	0	81	0.18	6.0	0.019
5	A	2.95	0.24	0.01	3.21	0.30	2.09	6.41	8.80	0	3	73	2.86	4.3	0.085
	B	7.80	0.15	0.92	11.34	0.65	2.28	20.21	23.15	4	3	87	0.69	4.3	0.075
6	A	3.65	0.72	0.09	6.83	0.40	1.81	11.29	13.49	1	3	84	2.19	4.3	0.084
	B	6.90	0.16	0.39	22.51	0.00	2.64	29.97	32.60	1	0	92	0.17	6.2	0.135

Table 4.8: Chemical analysis of the soils at Bungonia 2.

		Exchange Complex Data ($cmol.kg^{-1}$)								%				pH	Electrical Conductivity
Sample	Horizon	Ca^{2+}	K^{+}	Na^{+}	Mg^{2+}	Al^{3+}	H^{+}	TEB	CEC	ESP	EAP	BS	Organic Carbon	1:5 soil/solution ratio	($dS.m^{-1}$)
1	B	1.99	0.15	4.37	5.88	0.00	1.50	12.39	13.89	31	0	89	0.46	5.6	0.000
2	B	2.54	0.12	4.38	7.38	0.00	1.71	14.42	16.13	27	0	89	0.12	5.3	0.002
3	B	5.63	0.24	0.86	11.12	0.00	1.65	17.85	19.51	4	0	92	0.30	4.8	0.095
4	B	6.48	0.37	0.40	8.43	0.00	1.85	15.69	17.55	2	0	89	1.67	5.2	0.144
5	A	9.88	0.36	0.62	17.87	0.00	1.77	28.73	30.50	2	0	94	0.55	6.0	0.140
	B	4.16	0.12	1.09	7.95	0.00	1.26	13.32	14.58	7	0	91	0.16	4.7	0.085
6	B	3.66	0.08	0.96	5.21	0.00	1.41	9.91	11.32	8	0	88	0.07	5.4	0.210

Table 4.9: Chemical analysis of the soils at Bungonia 3.

		Exchange Complex Data ($cmol.kg^{-1}$)								%				pH	Electrical Conductivity
Sample	Horizon	Ca^{2+}	K^{+}	Na^{+}	Mg^{2+}	Al^{3+}	H^{+}	TEB	CEC	ESP	EAP	BS	Organic Carbon	1:5 soil/solution ratio	($dS.m^{-1}$)
1	A	4.63	0.24	1.46	12.67	0.00	1.94	19.00	20.94	7	0	91	0.68	4.5	0.100
	B	5.36	0.14	4.66	18.39	0.00	1.71	28.55	30.26	15	0	94	0.03	4.7	0.000
2	A	0.59	0.04	0.03	0.56	0.00	1.04	1.22	2.26	1	0	54	0.26	4.4	0.065
	B	1.29	0.16	0.82	7.70	0.00	1.31	9.97	11.28	7	0	88	0.13	4.3	0.200
	C	0.66	0.08	3.34	4.92	0.00	1.49	9.00	10.49	32	0	86	0.01	4.8	0.001

4.2.3 Statistical Analysis on Soil Parameters

Linear regression analysis was applied to determine if there were any relationships between the various physical and chemical properties in the soil samples. An analysis of variance test (ANOVA) was then performed to test the significance of the linear regression which resulted in either accepting or rejecting the null hypothesis at a 95% confidence level. Note that the coefficient of determination (R^2) used by 'Microsoft Excel'™ to calculate regression trendlines is not an adjusted R^2 value, and some of the data was transformed prior to analysis. The linear regression curves for each hypothesis tested are illustrated in Figure 4.5 and Figure 4.6, and the statistical data presented in Table 4.10. A matrix consisting of R^2 values was also conducted on different soil parameters (see Table 4.11).

The hypothesis tested was:

H_o: The independent variable (X) has no effect upon the dependent variable (Y).

H_A: The independent variable (X) has an effect upon the dependent variable (Y).

Table 4.10: Summarised statistical analysis conducted on soil samples from the three sampling sites. ^{ABC} represents all three horizons, ^{A} is the A horizons and ^{B} the B horizons.

Independent Variable (X)	Dependent Variable (Y)	Linear Regression Equation	(R^2)	(1-R^2)	P Value	Analysis of Variance
TEB	CEC	Y = 0.9882x + 2.369	0.9842	0.0158	P<0.001	Reject H_o
^{ABC}Moisture Content	Shear Strength	Y = -6.6363Ln(x) + 21.832	0.5095	0.4905	P>0.05	Accept H_o
^{A}Moisture Content	Shear Strength	Y = -6.1089Ln(x) + 22.541	0.4952	0.5048	P>0.05	Accept H_o
^{B}Moisture Content	Shear Strength	Y = -5.156Ln(x) + 17.862	0.2656	0.7344	P>0.05	Accept H_o

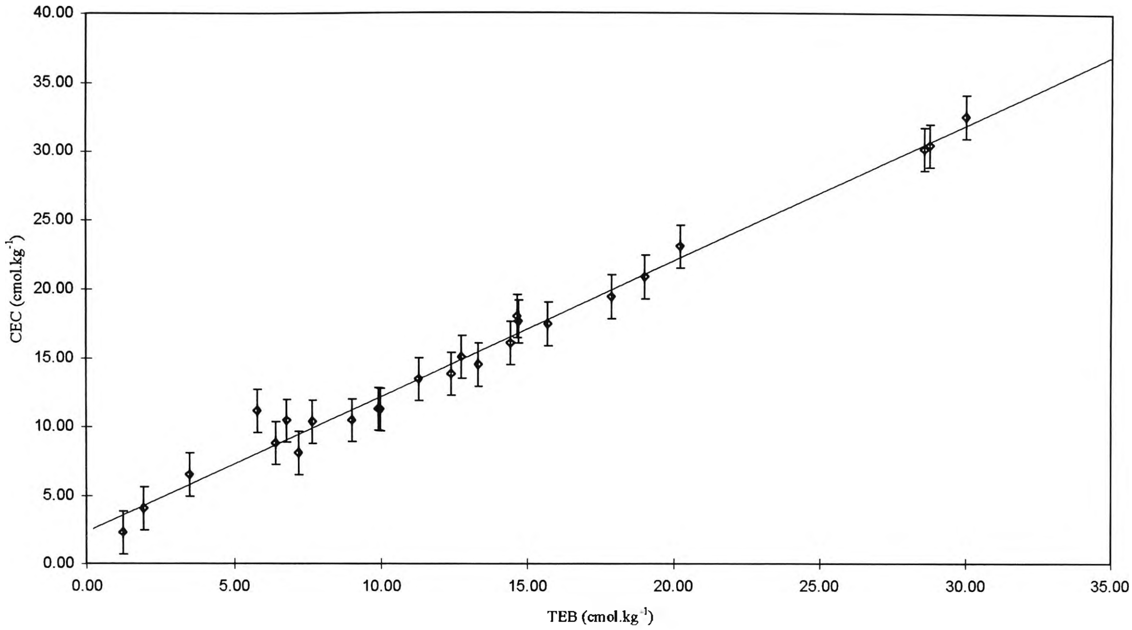

Figure 4.5: Linear regression curve for TEB v CEC at the three sites.

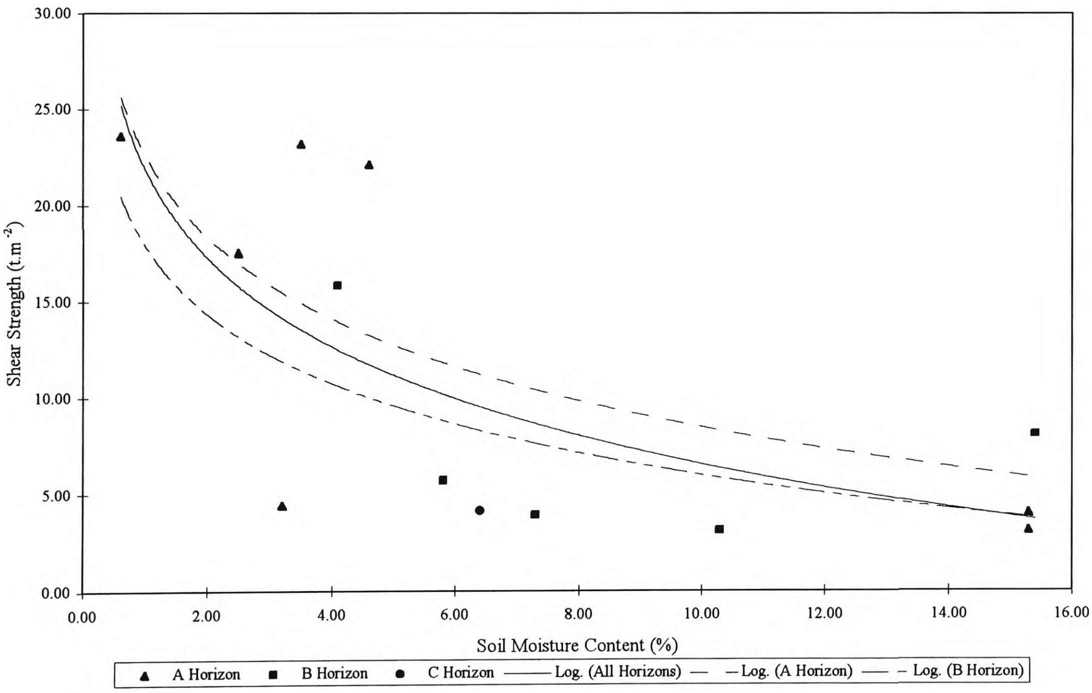

Figure 4.6: Linear regression curve for soil moisture content v shear strength at the three sites.

Table 4.11: R^2 matrix describing the relationship between different soil parameters.

	pH	EC	ESP	EAP	Organic Matter	CEC	TEB
pH		0.0383	0.0070	0.2819	0.1406	0.3633	0.3829
EC	0.0383		0.3887	0.0105	0.2845	0.0139	0.0267
ESP	0.0070	0.3887		0.0425	0.3506	0.0312	0.0431
EAP	0.2819	0.0105	0.0425		0.1611	0.1908	0.2409
Organic Matter	0.1406	0.2845	0.3506	0.1611		0.1110	0.1472
CEC	0.3633	0.0139	0.0312	0.1908	0.1110		0.9842
TEB	0.3829	0.0267	0.0431	0.2409	0.1472	0.9842	

The ANOVA concluded that TEB has a very significant effect upon the CEC of the soil samples, and that soil moisture content and shear strength have a non-significant association given by the R^2 values (see Table 4.10). This could be explained by the small number of sampling points (13) due to the dry weather which resulted in a low R^2 value. The mechanical strength of soil is also controlled by adsorbed cations, water content, clay content and dispersive clay (Barzegar *et al*, 1994).

4.3 GULLY CLASSIFICATIONS

The three sites were classified according to the method described by Crouch and Blong (1989) of sidewall morphology (Figure 4.7), sidewall activity and sidewall processes. The sidewall activity classification system used is related to the amount of ground cover present. Dominant sidewall processes include fluting, wall failure, seepage and overfalls.

4.3.1 Sidewall Morphology

At *Winston Gully*, four sidewall morphologies were identified: vertical; sloping; benched; and faceted. The location and extent of the morphologies identified within the gully are indicated in Figure 4.8.

The majority of the gully's sidewalls consist of vertical slopes (greater than 65°), with a maximum height of approximately 12 m. The head of the gully consists of large blocks of soil which have collapsed from the walls, resulting in a faceted (Fa/Fb) morphology. A 50 m section along the southern wall of the gully is benched with isolated sections of sloping banks.

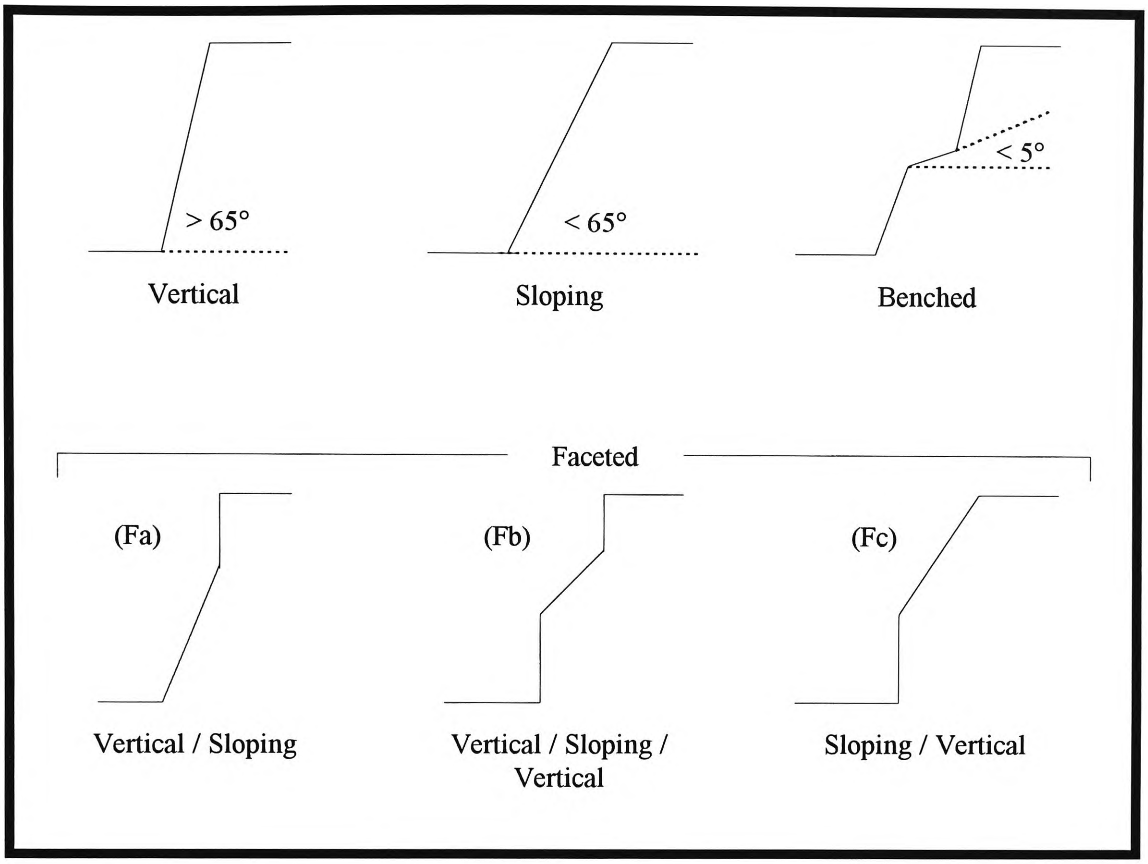

Figure 4.7: Crouch and Blong's (1989) classification of gully sidewalls.

The Bungonia 2 site consists of primarily sloping walls, with isolated sections of 3 m vertical and faceted (Fa/Fb) gully walls. Bungonia 3 consists of gently sloping 2.5 m sidewalls with vegetation cover over most of the gully.

4.3.2 Sidewall Activity

Sidewall erosional activity is classified according to the percentage vegetation cover over an area. The three categories are defined as active (< 20% ground cover), semi-active (20–70% ground cover) and stable (> 70% ground cover).

The majority of *Winston Gully* has active sidewalls with less than 20% ground cover. Those sections of the gully which are semi-active or stable generally exist where the gully is under bedrock control (Figure 4.9). This depicts that the gully sidewalls contain less than 20% ground cover and is an extremely active gully.

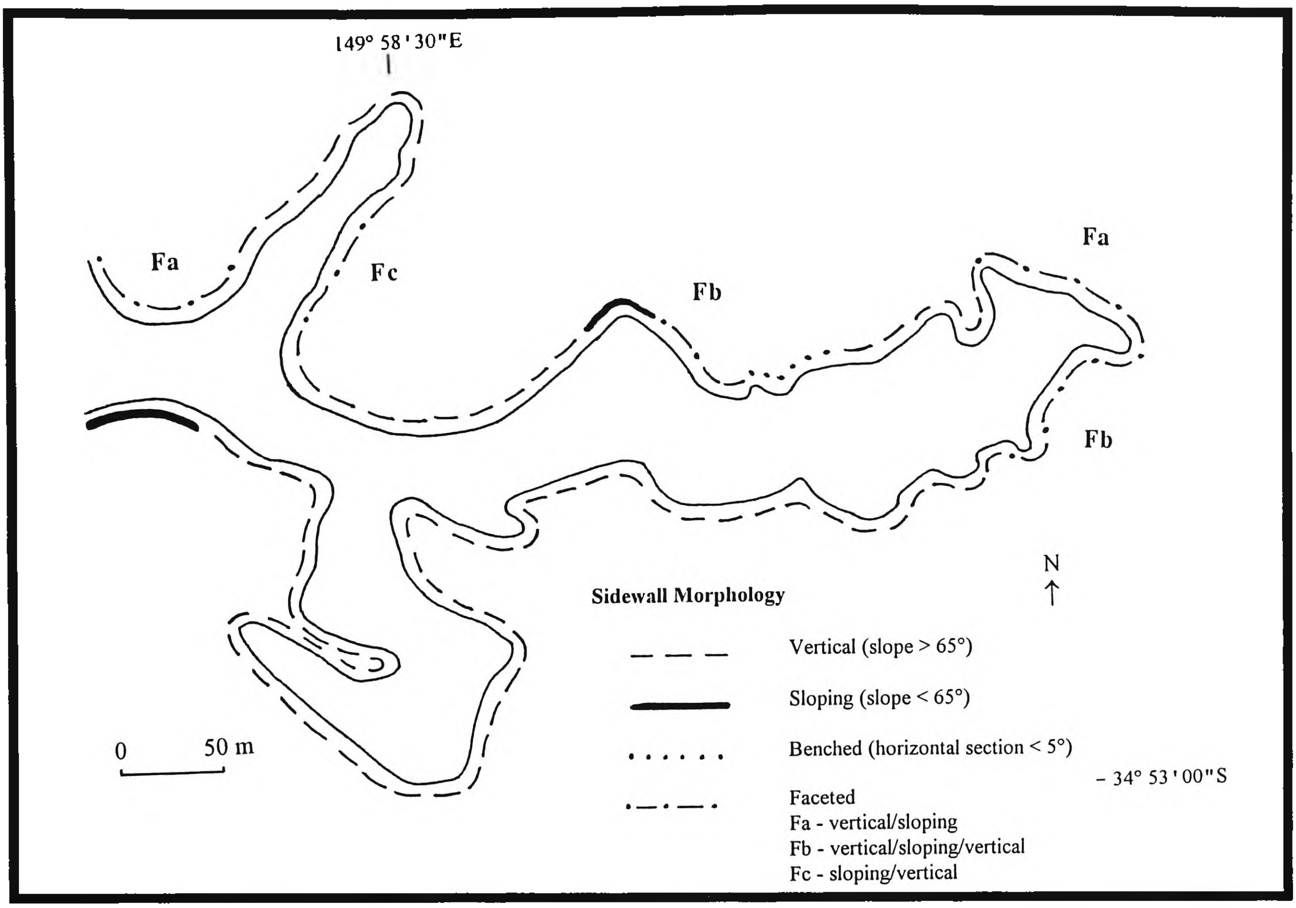

Figure 4.8: Sidewall morphology at *Winston Gully*.

Bungonia 2 is primarily active, with less than 20% ground cover on the sodic soils (Table 4.8). The Black Clay and Quaternary Orange Sand profile is classified as semi-active with 20–70% ground cover (Plate 3.2). At Bungonia 3, the sidewalls are stable due to the ground cover (mainly grass) dominating the area (Plate 3.4). Sites 2 and 3 showed a significant increase in vegetation growth after some mid-year rainfall, whereas *Winston Gully* had little increase in vegetation cover.

4.3.3 Dominant Sidewall Processes

The sidewall processes identified at *Winston Gully* include flutes, wall failure, seepage and overfalls (Figure 4.10), which are described in Table 4.12. The dominant process identified was seepage by subsurface erosion, which occurs at the head and along the southern section of the gully. Fluting is evident within the gully, ranging from weakly developed to moderately developed flutes in the north and south. Overfalls such as vertical walls with overhanging lips, undermining, the presence of scour channels and cave development in one soil horizon, are also evident at *Winston Gully*. Wall failure consists mainly of soil fall, with toppling (vertical wall and toppled blocks) apparent at the head and southern section where subsurface erosion is present.

Wall failure due to soil fall and overfalls consisting of vertical walls with overhanging lips dominate the sidewalls at Bungonia 2 (Plate 3.3). Weakly formed flutes and gently sloping sidewalls (Plate 3.4) are present at Bungonia 3.

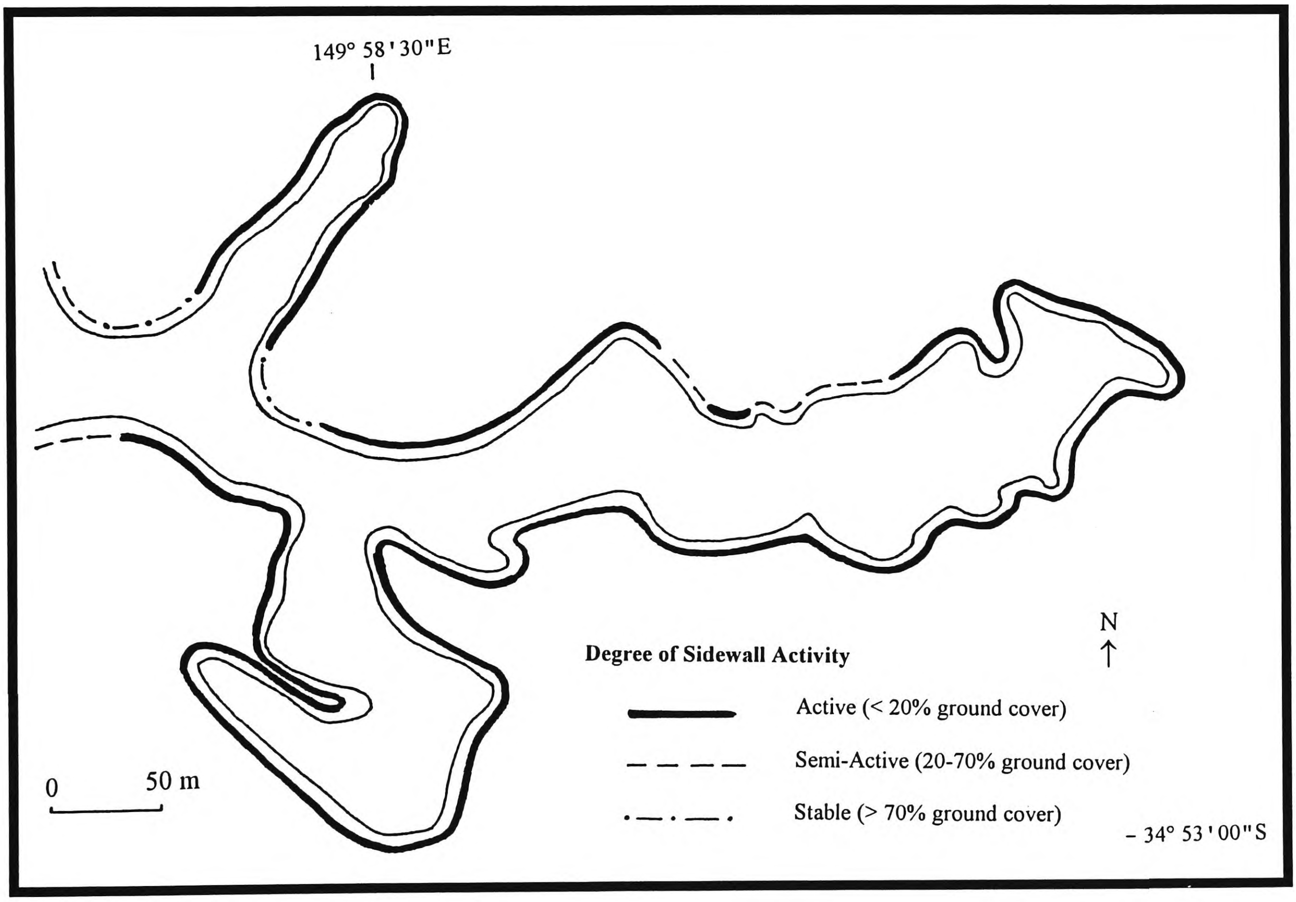

Figure 4.9: Degree of sidewall activity at *Winston Gully*.

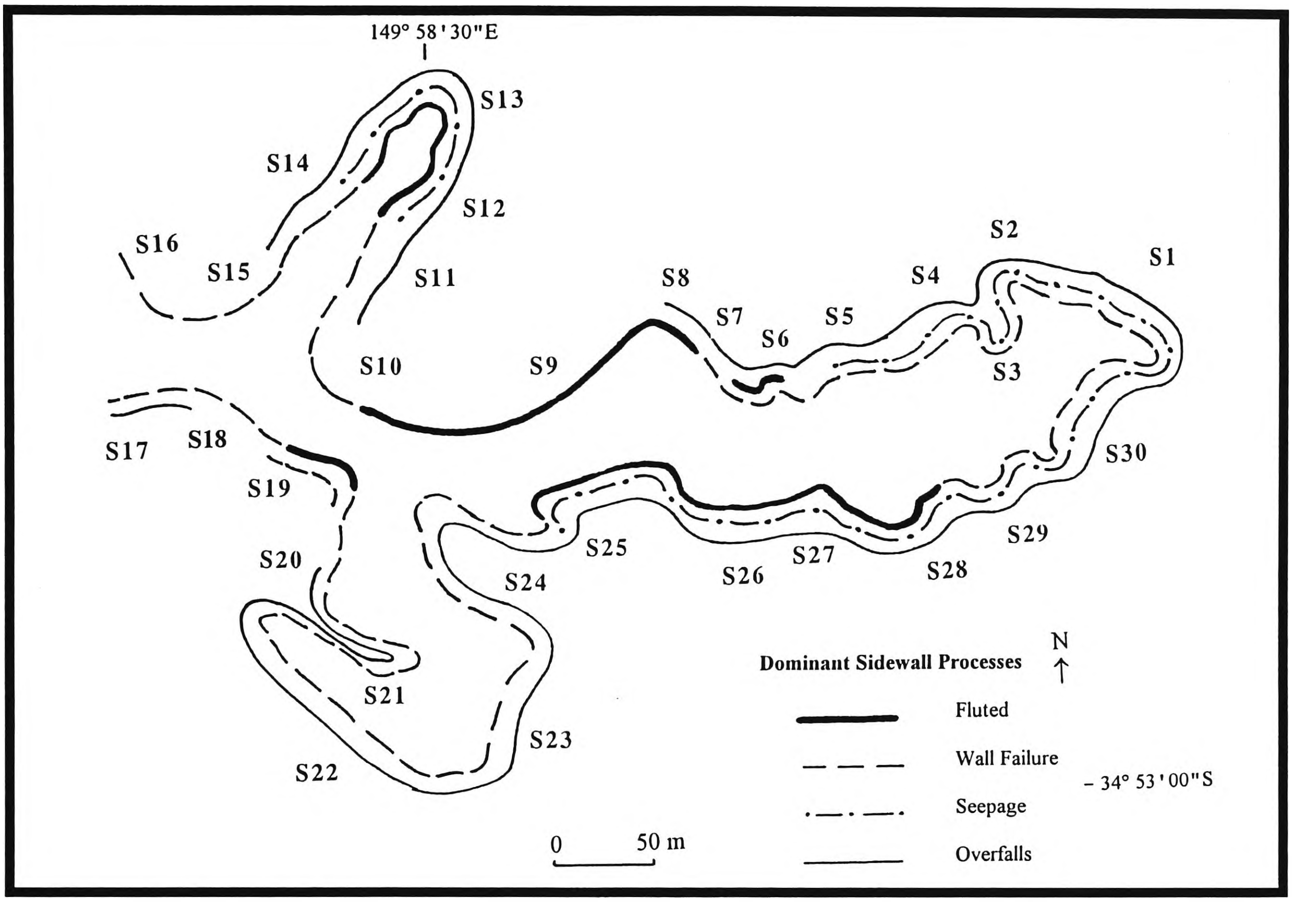

Figure 4.10: Dominant sidewall processes identified at *Winston Gully.*

Table 4.12: Summary of the dominant sidewall processes occurring at *Winston Gully*.

Site	Dominant Sidewall Processes
S1	Vertical wall and toppled blocks; subsurface seepage; vertical wall with overhanging lip; scour channel and cave development in one horizon.
S2	Vertical wall and toppled blocks; subsurface seepage; vertical wall with overhanging lip; undermining; scour channel and cave development in one horizon.
S3	Weak flutes; soil fall and scour channel.
S4	Soil fall; subsurface seepage; vertical wall with overhanging lip and scour channel.
S5	Moderately developed flutes; soil fall; subsurface seepage and cave development in one horizon.
S6	Sliding slab; soil fall and scour channel.
S7	Moderately developed flutes; soil fall; vertical wall with overhanging lip and scour channel.
S8	Sliding slab; soil fall and vertical wall with overhanging lip.
S9	Weak flutes.
S10	Undermining by more than 0.15 m.
S11	Weak flutes; vertical wall and toppled blocks; soil fall; subsurface seepage; undermining by more than 0.15 m; scour channel and cave development in one horizon.
S12	Soil fall and vertical wall with overhanging lip.
S13	Soil fall; vertical wall with overhanging lip and undermining by more than 0.15 m.
S14	Soil fall.
S15	Soil fall.
S16	Circular slip.
S17	Soil fall and vertical wall with overhanging lip.
S18	Soil fall.
S19	Weak flutes and soil fall.
S20	Soil fall and vertical wall with overhanging lip.
S21	Soil fall and vertical wall with overhanging lip.
S22	Soil fall and vertical wall with overhanging lip.
S23	Soil fall and vertical wall with overhanging lip.
S24	Soil fall and vertical wall with overhanging lip.
S25	Weak fluting; soil fall; subsurface seepage and scour channel.
S26	Weak fluting; vertical wall and toppled blocks; subsurface seepage and undermining by more than 0.15 m.
S27	Weak fluting; vertical wall and toppled blocks; subsurface seepage and cave development in one horizon.
S28	Weak fluting; vertical wall and toppled blocks; subsurface seepage; undermining by more than 0.15 m and scour channel.
S29	Vertical wall and toppled blocks; soil fall; subsurface seepage; undermining by more than 0.15 m and cave development in one horizon.
S30	Vertical wall and toppled blocks; soil fall; subsurface seepage; undermining by more than 0.15 m and cave development in one horizon.

4.4 SIDEWALL EXTENSION PROCESSES

4.4.1 Channel Scouring

Channel flow is the mechanism by which the eroded material from the sidewalls of the gully is removed from the system and transported further downstream. Channel flow is an important erosive process in the development of sidewalls at *Winston Gully*. The flow of the channel meanders from sidewall to sidewall, undercutting and scouring the sidewalls of the gully (Plate 4.1). As the flow undermines the sidewalls, the dispersive soil eventually fractures and collapses. The mobilisation of sediment eroded from the gully sidewalls and headwall was observed during rainfall events. This sediment is composed of unconsolidated material lacking structure, or significant quantities of organic matter or plant nutrients. Channel scouring and meandering was not apparent at Bungonia 2 or either at Bungonia 3 due to the different physical characteristics of these sites.

Plate 4.1: Channel scouring and undermining at the base of the gully floor.

4.4.2 Fluting

Flutes, or cathedrals, are described as vertical elongated tubes narrowing towards the top, furrowing into the sidewall of the gully. The dispersive soils at *Winston Gully* exhibit fluting, with evidence of weakly developed flutes at Bungonia 3.

The development and destruction of flutes at *Winston Gully* is similar to the sequence of events describing those studied by Veness (1980). Fluting is initiated when rainwater dislodges soil particles from the sidewalls, removing further material by slaking and dispersion. Plate 4.2 illustrates the development of flutes in *Winston Gully*. Flutes generally develop from rill formation as long as the channel flow has sufficient energy to transport the sediment away from the base. Flutes up to 7 m in height are common along the sidewalls of *Winston Gully*. The flutes will continue to develop until the gully wall is undermined by scouring and soil collapse occurs, leaving a fresh surface for the cycle to begin again.

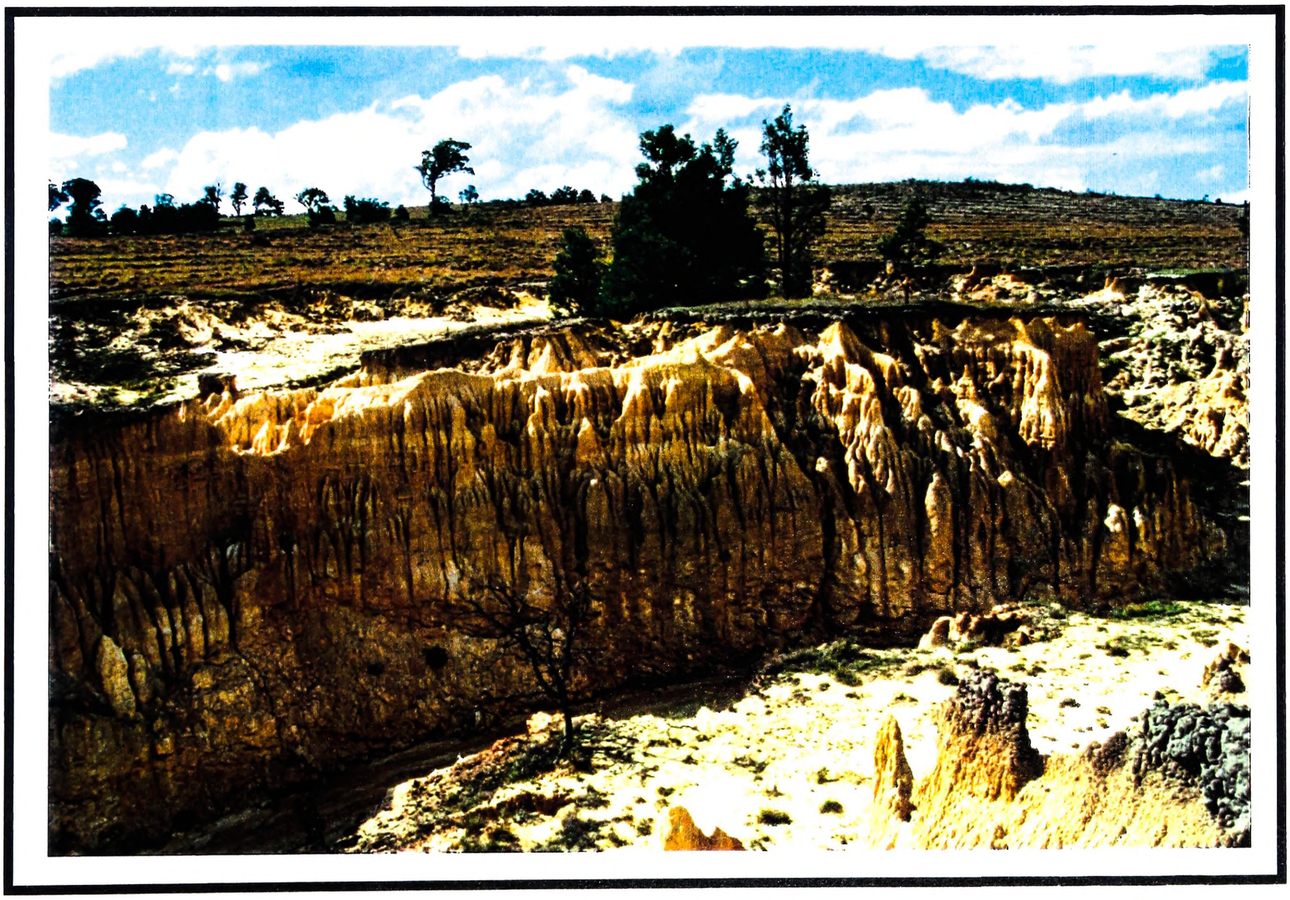

Plate 4.2: Active, moderately developed flutes along the sidewalls of *Winston Gully* approximately 7 m in height.

4.4.3 Pinnacle Erosion

Pinnacles are associated with very deep vertical rills in the sides of a gully which rapidly cut back until they join, leaving 'isolated' pinnacles in the gully floor. These pinnacles are found along the sidewalls and floor of *Winston Gully*, extending 8 to 10 m vertically. The pinnacles within the gully are associated with highly dispersive sodic soils containing high exchangeable sodium levels. Due to a high evaporation rate and rapid drying of the surface soil, a hardsetting A horizon forms the cap of the pinnacle (Plate 4.3). The gully walls are also severely undercut by flowing water resulting in tunnels being formed beneath some of the pinnacles as illustrated in Plate 4.4.

Plate 4.3: Isolated pinnacle consisting of a hard capped A horizon overlaying a highly dispersive B horizon.

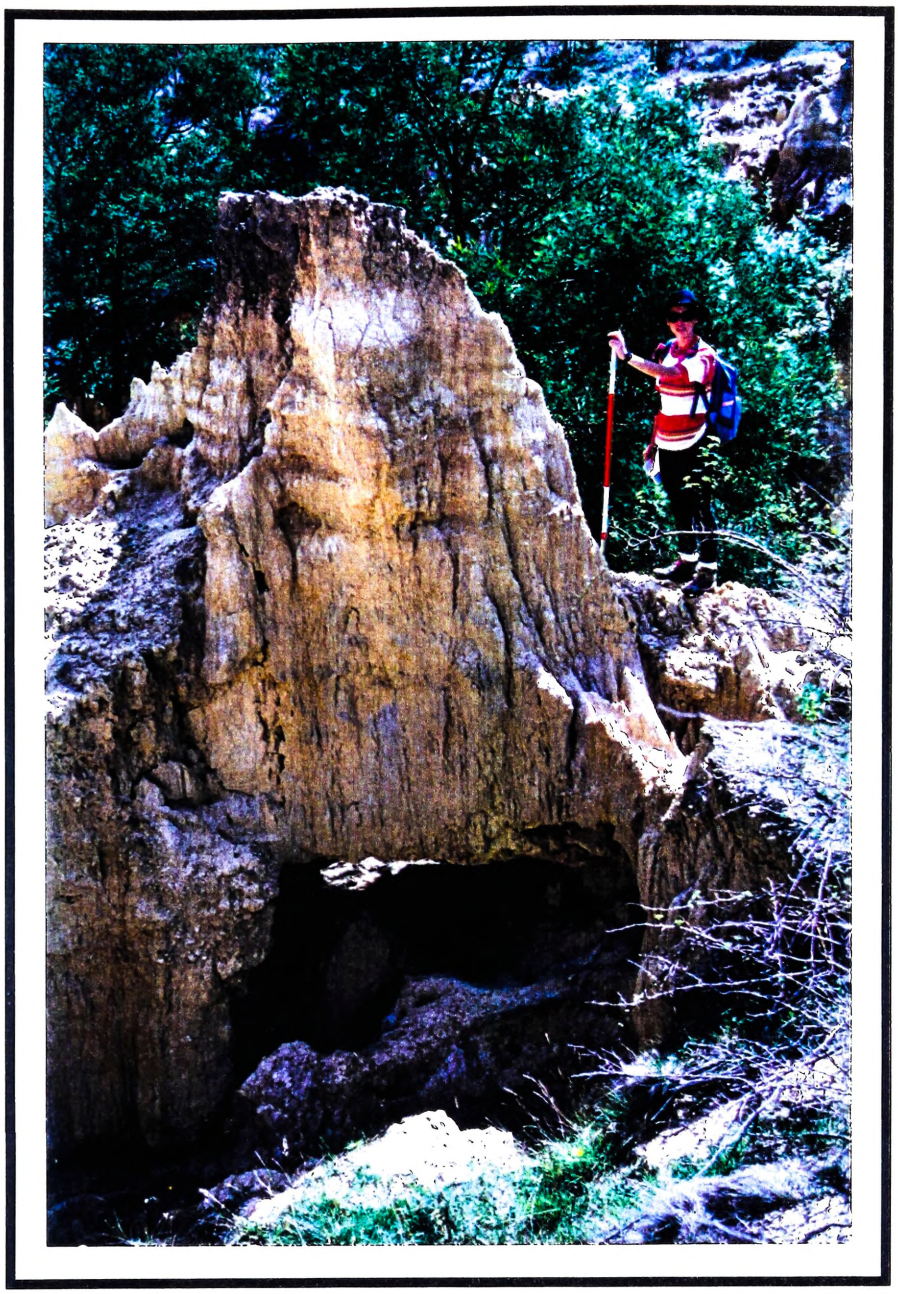

Plate 4.4: Horizontal tunnelling occurring underneath a pinnacle.

4.4.4 Sidewall Fracturing and Collapse

The sides of the gully originate as vertical walls exposed by overfall erosion. Erosion occurs under the influence of water and gravity until the gully sides are reduced to a relatively stable slope. The sidewalls of *Winston Gully* erode by the combined effect of rainsplash impact, overland flow, subsoil flow, channel flow and sidewall fracturing. Sidewall failure is due to water seeping into cracked soil as a result of prolonged periods of dry weather (Plate 4.5). Extensive cracks were observed due to sidewall fracturing, which eventually result in the walls collapsing (Plate 4.6).

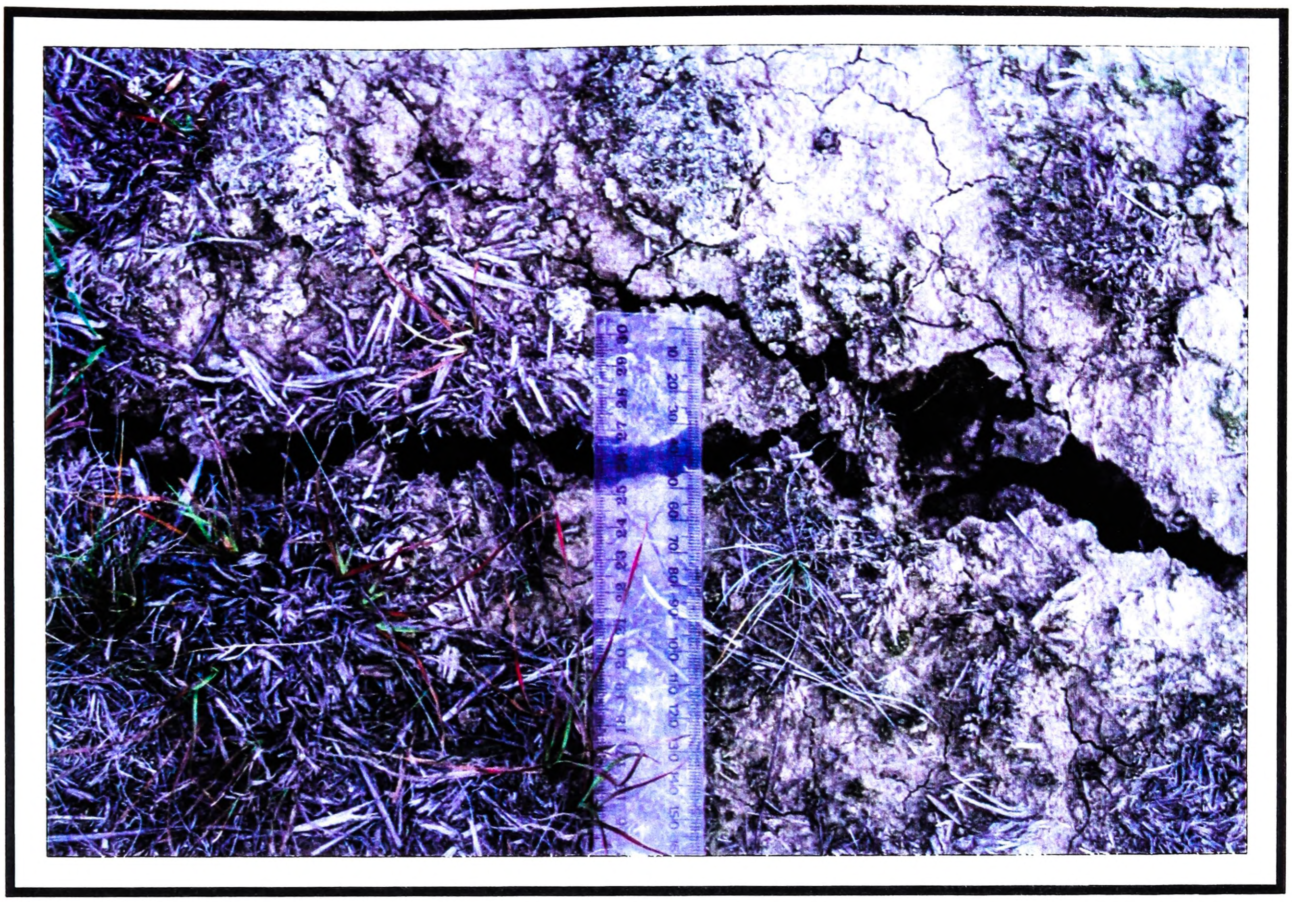

Plate 4.5: The cracks in the soil provided an easy access for the movement of water through a dispersive B horizon.

Keyline contour ripping and mounding was conducted in 1995 by the Department of Land and Water Conservation (Goulburn) (Plate 1.1) aimed at limiting the amount of surface water entering the B horizon. However, the ripping has intersected the *Winston Gully* sidewalls along the left bank producing large surface cracks, allowing water to move freely into the impermeable B horizon. The majority of the well developed tunnels are located along the southern section where the contour ripping has accelerated the processes of erosion within the gully.

Plate 4.6: Sidewall collapse resulting in the accumulation of sediment within the gully floor.

4.4.5 Tunnelling

Tunnelling or piping is an erosive process involving the removal of subsurface soil through hydraulic action, resulting in the formation of underground tunnels. Tunnelling is associated with a duplex sodic soil characteristic of a resistant, hard silty loam crust (A horizon), poor vegetation cover, a structureless pale grey silty loam A_2, and a yellow, highly dispersive, and impermeable B horizon (Plate 4.7).

Three characteristic tunnel formations have been recognised at *Winston Gully* similar to those identified by Crouch (1976).

1. Shallow tunnels formed in the A_2 horizon along the sidewalls at the gully head (Plate 4.8).

2. Deep tunnels located in the B horizon extending in both vertical and horizontal directions along the southern wall only (Plate 4.7).

3. Tunnels formed at the base of the gully floor consisting of lesser dimensions than those in the B horizon, due to the dispersive action (Plate 4.9).

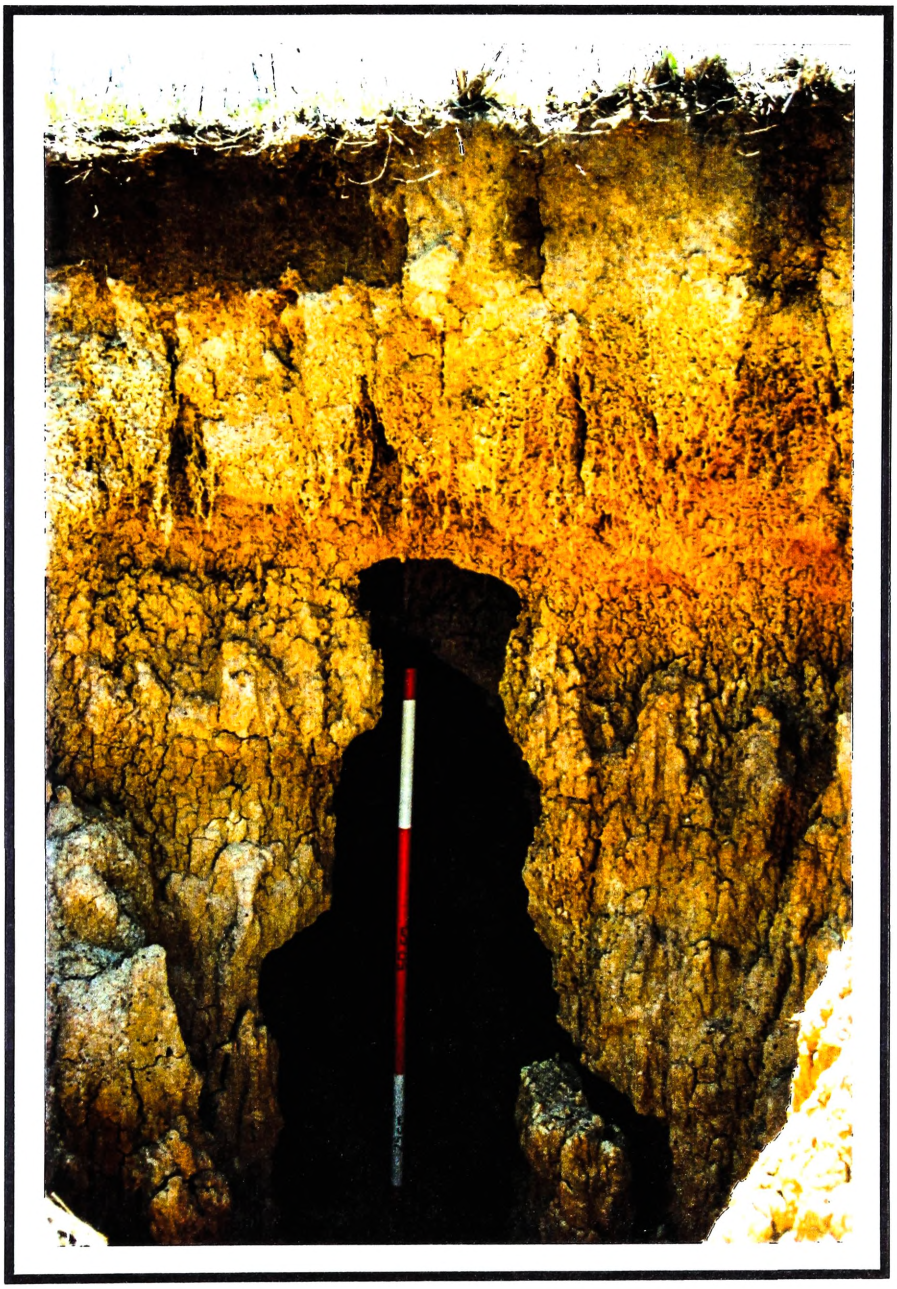

Plate 4.7: Soil profile illustration associated with tunnelling and "cave" development in the B horizon.

Plate 4.8: Shallow tunnels formed in the A_2 horizon.

Tunnels were randomly measured at *Winston Gully* to determine the cross-sectional area of these structures (Appendix A.11). The majority of tunnels occur along the southern sidewalls of the gully where subsurface erosion is the dominant erosive process. The areas of these tunnels range from a few square centimetres to approximately 1 m^2 (Plate 4.10). No tunnelling was evident at Bungonia 2 or Bungonia 3 due to the vegetation cover, lack of surface cracks and less dispersive soils at these sites.

Plate 4.9: Tunnels are also formed at the base of the gully floor in the horizontally laminated clays as illustrated in this plate.

Plate 4.10: A view from inside of a deep tunnel approximately 1.5 m in width and 3 m in depth.

4.4.6 Sediment Deposition

A considerable quantity of sediment has been deposited on the gully floor by the collapse of sidewalls and from tunnels. *Winston Gully* is active only during rainfall events, with the system being 'locked up' during periods of drought. During periods of rainfall, water flows laterally through the permeable B horizon through existing tunnels, or forming new tunnels. Fine particles of soil are mobilised and deposited either on the gully floor, or transported downstream. When the energy of the flow is insufficient to transport the sediment, the soil particles accumulate on the gully floor as unconsolidated sediment.

4.4.7 Other Processes

Sections of *Winston Gully* where bedrock is exposed along the sidewalls and floor are free of tunnels, fluting and pinnacles (Plate 4.11). Approximately 500 m downstream of the head the contemporary processes change. In this area the southern bank of the creek becomes stable forming a stable hill (Plate 4.12), and opposite this is a major slump which has existed since 1941 (Plate 4.13). In this section gullying and tunnelling are absent due to the changes in soil composition (Table 4.1) and vegetation cover.

Gullying is occurring at Bungonia 2 within a sodic soil (Plate 3.3 and Table 4.8), but located 50 m from Bungonia 2 the gully sidewalls are stable (Plate 3.2). Bungonia 3 exhibits minor contemporary erosive processes composed of small rills, some evidence of gullying and stable slopes (Plate 3.4).

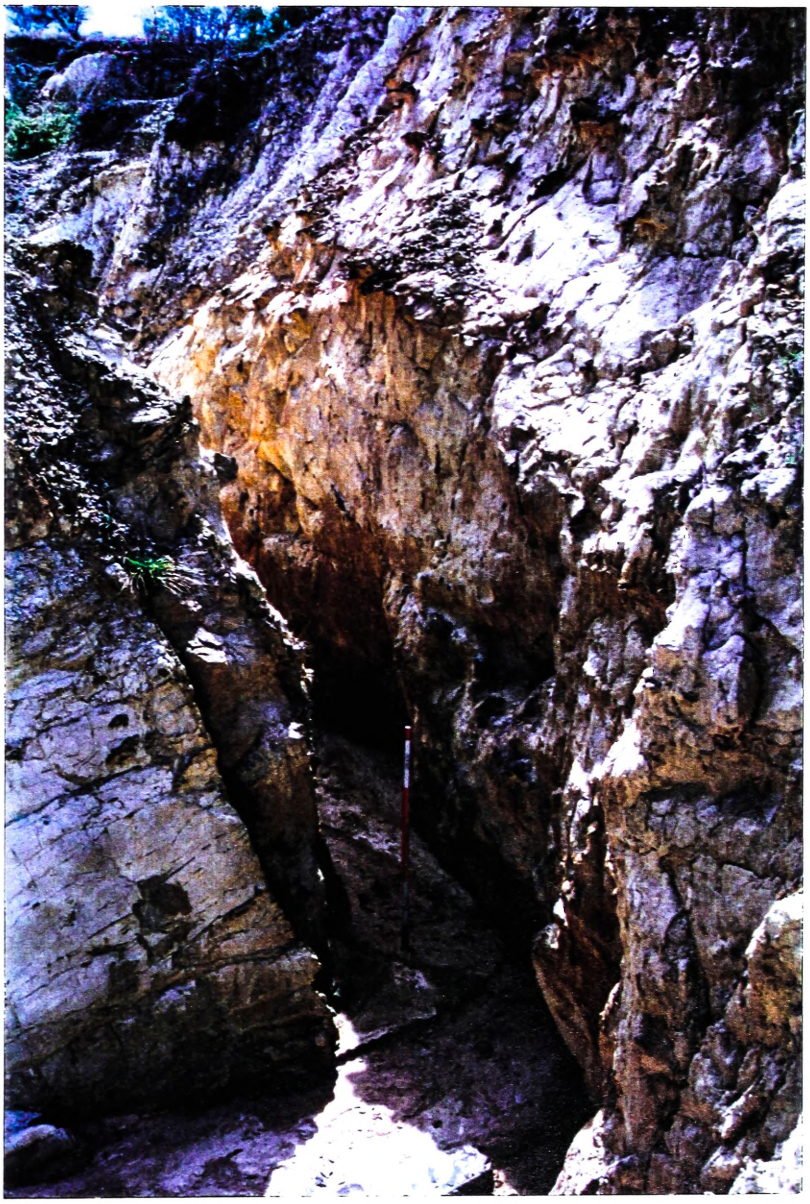

Plate 4.11: This deeper section of the gully is absent of erosive processes due to exposed bedrock control.

Plate 4.12: Stable hills form part of Limekiln Creek only 500 m downstream of the head of *Winston Gully*.

Plate 4.13: Opposite the stable hill (Plate 4.12), is a sidewall undergoing slumping.

4.5 HEADWALL EXTENSION PROCESSES

The development of *Winston Gully* is dependent upon the chemical characteristics and physical structure of the soils. Subsurface seepage is the primary erosion process occurring at the gully head. Overland flow, while still responsible for erosion, is less significant than subsurface flow in *Winston Gully*. The rate of the erosion is accelerated by the sparse vegetation cover and surface roughness which allows surface water to enter the B horizon. The gully head is advancing to the east, widening and becoming deeper during rainfall in the highly dispersive, unconsolidated parent material. The tunnelling is accelerating further growth of the gully head and sidewalls. Where subsurface flow lines intersect the gully walls, the soil becomes saturated and collapses (Plate 4.14).

It is obvious that there are several different processes occurring within *Winston Gully*. It is difficult to separate cause from effect with a combination of erosive processes present within the gully.

Plate 4.14: Slumping of the material looking up at the head of the gully due to advanced tunnel erosion.

4.6 CALCULATION OF EROSION RATES

From the cross-sections conducted at *Winston Gully* (Figure 3.2), the horizontal surface area removed by downcutting and sidewall retreat was calculated (Figure 4.11 to Figure 4.18). Only at the head of the gully (Figure 4.11) does the volume of soil removed by downcutting equal the volume of soil lost by sidewall retreat. This is due to the gully head being the 'newest' section of the gully. The cross-sections illustrate that the greatest volume of soil removed within the gully is due to sidewall retreat, and that channel downcutting is only significant in the early stages of erosion.

In the majority of geomorphic studies, gully headward extension has been considered as the major source of mobilised sediment. Work conducted by Crouch and Blong (1989); Edwards *et al* (1989) and Veness (1980) indicated, however, that sidewall extension of gullies produces more than 50 percent of the sediment mobilised during rainfall. This appears to be the situation at *Winston Gully*.

The Bungonia District was the subject of aerial surveys in 1941, 1967 and 1991, and these can be used to trace the growth of *Winston Gully* over a 50 year period. From 1941 to 1991, the head of the *Winston Gully* advanced approximately 200 m eastward at an average rate of 4 $m.yr^{-1}$. Sections of the gully head advanced by approximately 1.5 m during one rainfall event in 1995 alone.

The total volume of sediment eroded from *Winston Gully* (as of 1991) was calculated by dividing the gully into cells associated with each profile. The volume of sediment removed from each cell was given by the cross-sectional area of each profile (Figure 4.11 to Figure 4.18) multiplied by the cell length. Therefore, the total volume of sediment eroded from *Winston Gully* up to 1991 was approximately 120 000 m^3. Assuming an average bulk density of 1.66 $t.m^{-3}$ (Table 4.1), this represents approximately 200 000 t of sediment. Table 4.13 summarises the growth of the gully this century, based upon the assumptions that the growth of *Winston Gully* commenced in 1900, and that the increase in volume is proportional to the increase in area of the gully.

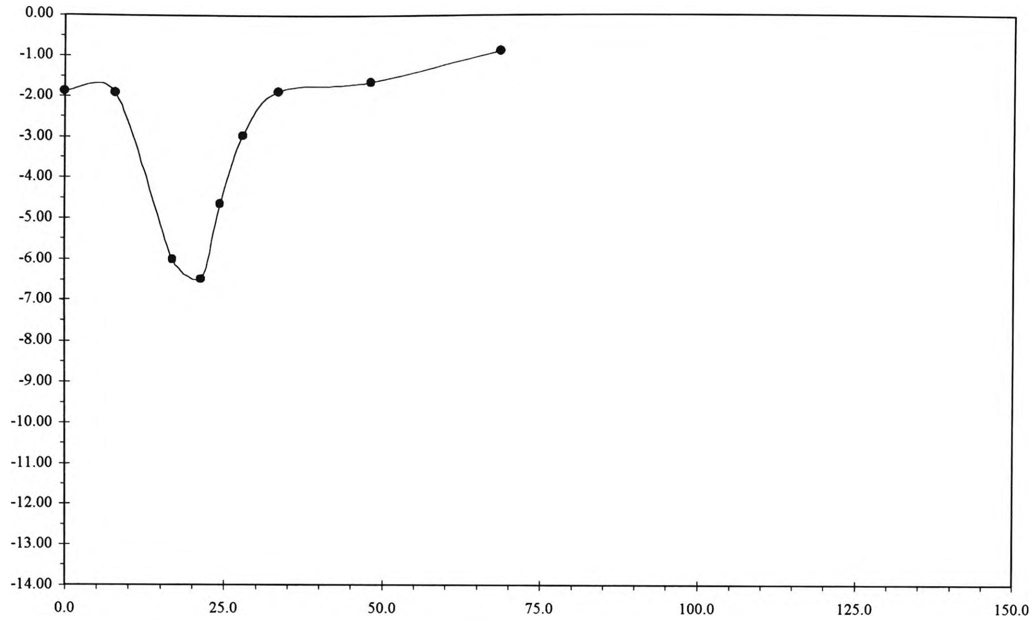

Figure 4.11: Profile 1. Downcutting area = 29 m^2 and sidewall retreat area = 29 m^2. (See Figure 3.2 for location of profile).

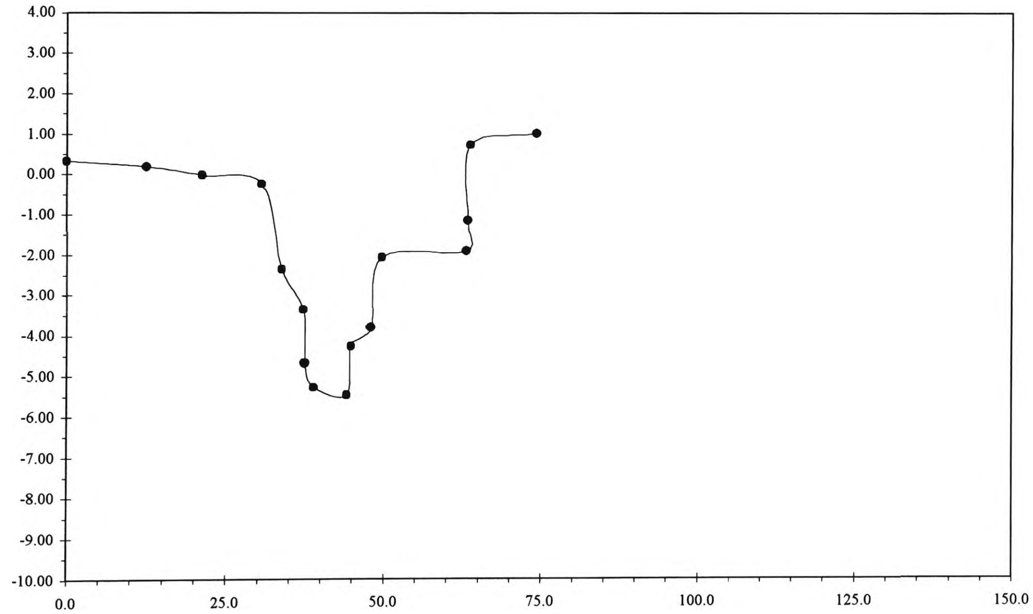

Figure 4.12: Profile 2. Downcutting area = 36 m^2 and sidewall retreat area = 81 m^2. (See Figure 3.2 for location of profile).

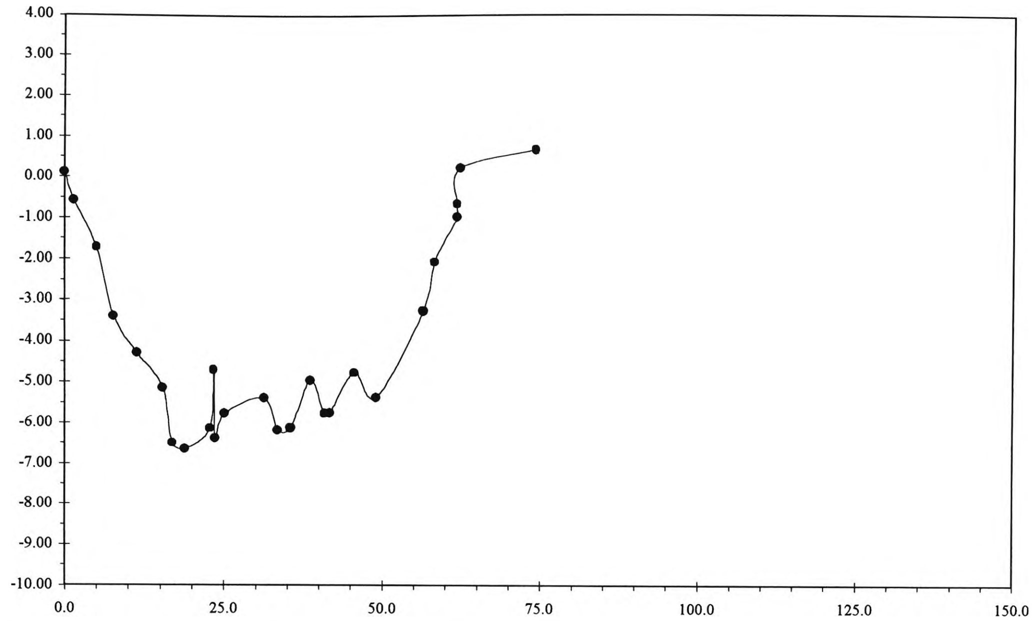

Figure 4.13: Profile 3. Downcutting area = 49 m^2 and sidewall retreat area = 214 m^2. (See Figure 3.2 for location of profile).

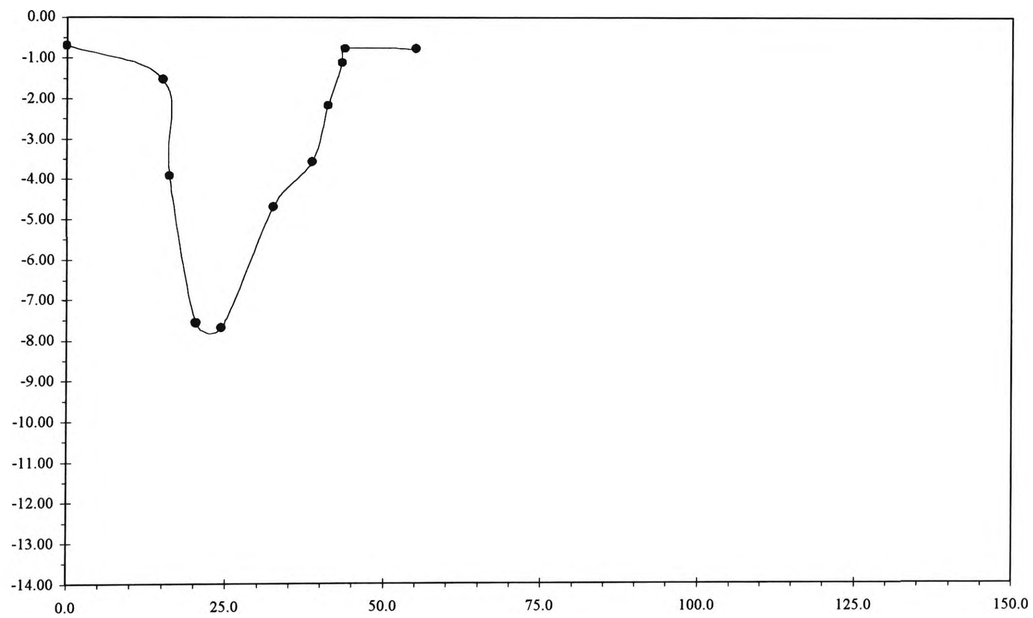

Figure 4.14: Profile 4. Downcutting area = 28 m^2 and sidewall retreat area = 91 m^2. (See Figure 3.2 for location of profile).

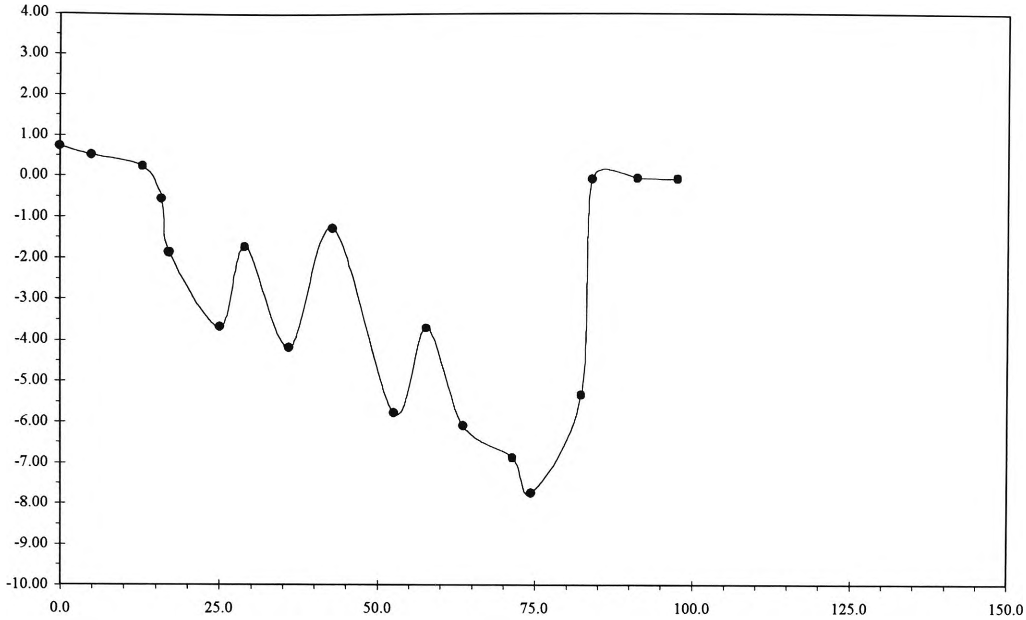

Figure 4.15: Profile 5. Downcutting area = 15 m^2 and sidewall retreat area = 281 m^2. (See Figure 3.2 for location of profile).

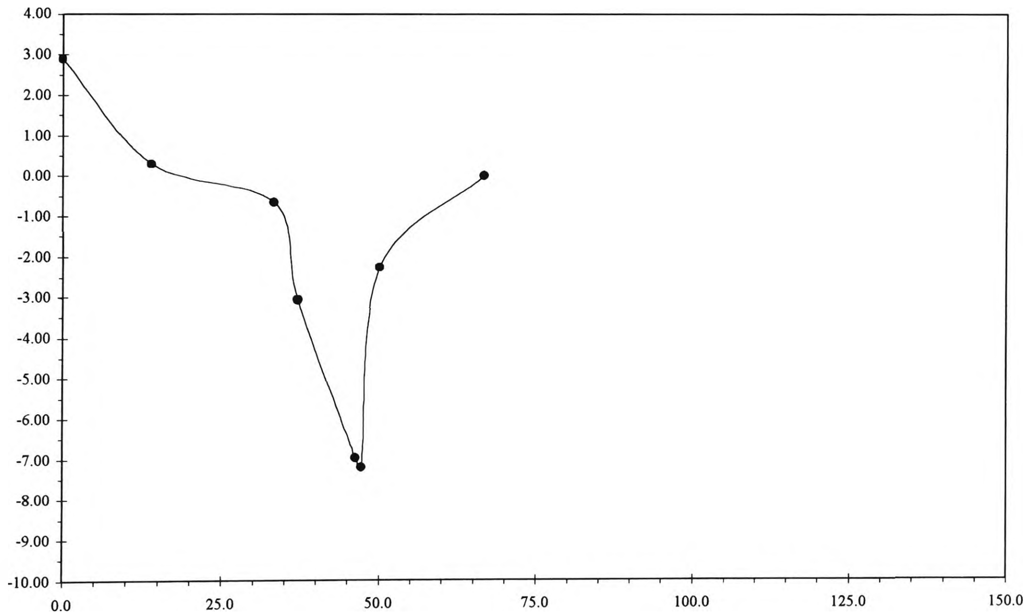

Figure 4.16: Profile 6. Downcutting area = 13 m^2 and sidewall retreat area = 57 m^2. (See Figure 3.2 for location of profile).

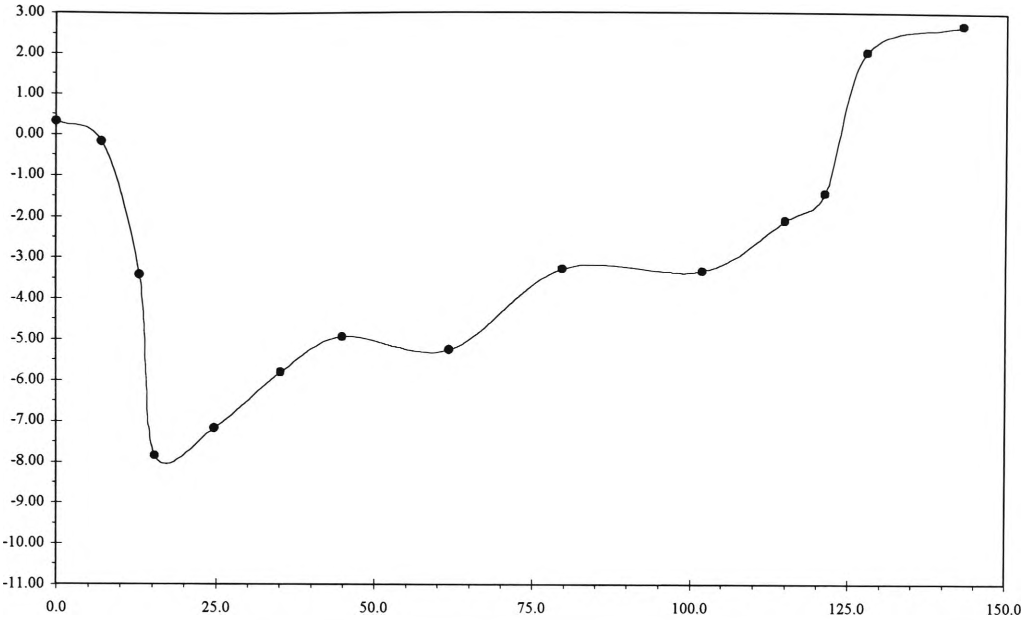

Figure 4.17: Profile 7. Downcutting area = 62 m^2 and sidewall retreat area = 275 m^2. (See Figure 3.2 for location of profile).

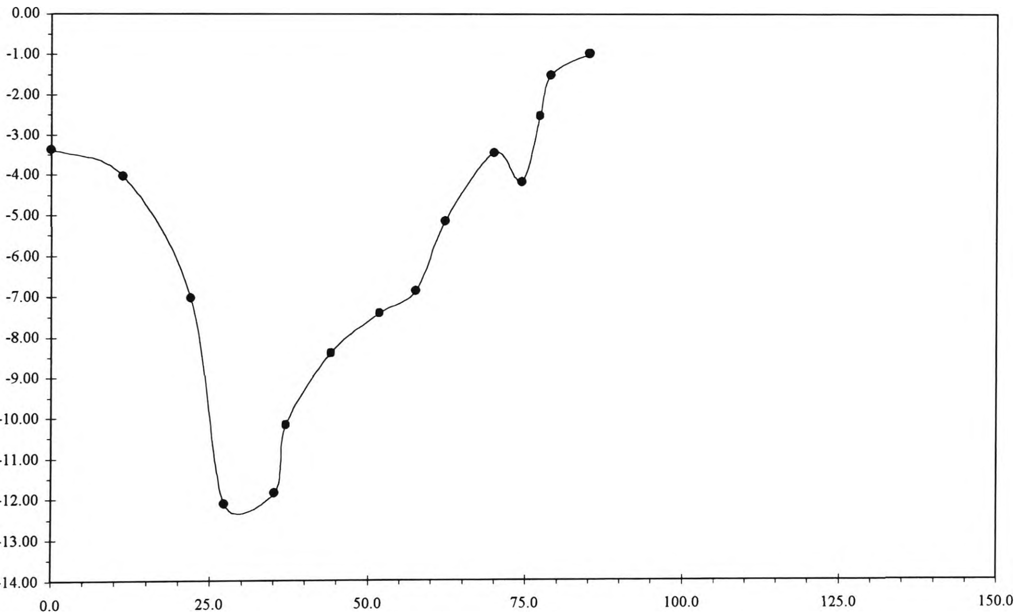

Figure 4.18: Profile 8. Downcutting area = 78 m^2 and sidewall retreat area = 232 m^2. (See Figure 3.2 for location of profile).

Table 4.13: Summarised table of estimated sediment loss from *Winston Gully*. The catchment of *Winston Gully* is approximately 1 km^2.

	1941	1976	1991
Area of gully (ha)	1.1	2.3	3.2
Rate of growth ($ha.yr^{-1}$)	0.03	0.05	0.06
Total volume of gully (m^3)	41 000	86 000	120 000
Total quantity of sediment lost (t)	68 000	143 000	200 000
Sediment yield ($t.km^{-2}.yr^{-1}$)	1 660	2 140	3 800

The sediment yield for *Winston Gully* is significantly greater than the yields reported for many catchments along the east coast of NSW. This result will be discussed further in Chapter 5.

5 DISCUSSION

5.1 THE RELATIONSHIP BETWEEN SOIL PROPERTIES AND WATER EROSION

Even though the three sites are subject to the same climatic conditions, differences in the physical and chemical properties of the soils have resulted in different erosion processes. Gully erosion is evident at each site, while tunnel erosion is present only at *Winston Gully*. Erosion generally follows a cycle of activity interspersed between extended periods of stability. This cycle roughly corresponds to the seasons, with the erosion generally occurring during the winter months when the most intense rainfall occurs (K. Cooper, *pers. comm.*, 1996). Based upon the gully profiles and aerial photographs, a total of approximately 200 000 t of sediment has eroded from *Winston Gully*.

Intense weathering over thousands of years and a lower degree of leaching of mineral salts has resulted in the formation of highly sodic soils in the Bungonia District (Wray, 1991). The mineralogy modifies the effects of sodicity and enhances the weathering process (Churchman *et al*, 1995). The ESP values range from 0–7% (non-sodic) for the A horizon to 15–47% (highly sodic) for the B and C horizons (Table 4.7 to Table 4.9). These results have been independently confirmed by Hart (1995) and Ku (1995), both of whom report high levels of sodium and magnesium present in the soils from *Winston Gully*.

The ESPs of the soils from the three study sites are much higher than ESP values reported in literature from other regions in NSW (e.g., Crouch *et al*, 1986). The highly dispersive sodic clays (kaolinite and illite) and high concentrations of exchangeable sodium and magnesium within the soils have led to increased severity of gullying and tunnelling present at the sites. Kaolinite and illite are known to be more susceptible to dispersion than other clays, and are frequently associated with tunnel erosion.

The majority of the subsoil lacustrine sediments were found to contain high concentrations of exchangeable sodium and magnesium ions, and low concentrations of calcium. Where the ratio of sodium to magnesium concentration was approximately 1:1, the ESP value was greater than 7% (Table 4.7 to Table 4.9), indicating sodic to highly sodic soils. In the presence of water, sodium and magnesium saturated clays swell until the clay particles eventually break apart, resulting in dispersion. The dispersed clay particles are then transported by subsurface flow through pores and channels in the soil profile. Soil sodicity results in a decrease in the soil permeability as the dispersed soil particles block soil pores, promoting the formation of tunnels in the soil profile (Plate 4.7 to Plate 4.10). The elevated levels of exchangeable sodium cause the aluminosilicate minerals (clays) to swell and disperse in water (Churchman *et al*, 1995) at ESP values as low as 10% (Frenkel *et al*, 1978).

The concentration of exchangeable calcium was extremely low (mean = 0.52 $cmol.kg^{-1}$) in the upper half of *Winston Gully,* which had little vegetation cover on either the gully floor or sidewalls. The calcium concentration was significantly higher in the lower half of the gully (mean = 4.12 $cmol.kg^{-1}$) due to the presence of calcium carbonate nodules at sampling sites 4 to 6 (Table 4.7). These nodules were identified by Wray (1991) as pedogenic calcrete nodules formed as a result of solutional and the reprecipitation of calcium carbonate from groundwater over thousands of years. The exchangeable calcium was generally higher for Bungonia 2 (mean = 4.91 $cmol.kg^{-1}$) and Bungonia 3 (mean = 2.56 $cmol.kg^{-1}$) (Table 4.8 to Table 4.9). Both these sites had significantly more vegetation cover than upper *Winston Gully.* No calcium carbonate nodules were found at either Bungonia 2 or Bungonia 3.

The soils of the study sites are primarily composed of clay and silt (mean of 34% and 27% respectively), with fine sands forming the remainder of the soil (Table 4.1 to Table 4.3). Aggregates within the B horizon (especially those < 63 μm) were found to be unstable and predisposed to slaking when wet. The large scale slumping observed during rainfall events is the result of the instability of the soil when wet. This confirms Sumner's (1993) observation that the extent of slumping increases with a soils tendency to slake.

Barzegar *et al* (1994) found that the shear (tensile) strength is strongly related to spontaneously dispersive clays ($R^2 = 0.99$). While the dispersive potential of clays at Bungonia could not be tested due to lack of equipment, Barzegar *et al* (1994) states that dispersive soils with a high clay content and ESP have a higher shear strength upon drying. The results obtained from this study indicate that the conclusions of Barzegar *et al* (1994) are applicable to each of the study sites.

The relationship of organic matter to dispersion is uncertain. Churchman *et al* (1995) cite numerous examples of researchers reporting that organic matter suppresses the tendency of clay to swell and disperse, while others report that it enhances soil dispersion. The soil samples from the three sites contain less than 2% organic carbon (Table 4.7 to Table 4.9), especially the subsurface horizon at *Winston Gully* where tunnelling is present (mean = 0.60% for sites 1 to 3). The lack of organic matter would indicate that the soil aggregates are unable to maintain their structure, thus becoming unstable when wet.

Black and Campbell (1982); Gillman (1981) and Gillman and Bell (1978) have each reported a strong relationship between the ionic strength and electrical conductivity of soil solutions. The relationships between the empirical ionic strength of the soil solution and the electrical conductivity of the Bungonia soils are summarised in Table 5.1.

Table 5.1: Empirical determination of ionic strength (I) of Bungonia soil solutions using the electrical conductivity (EC) values of this study.

	Linear Regression Equation for Ionic Strength	Minimum* Ionic Strength (I)	Maximum Ionic Strength (I)
Gillman and Bell (1978)	I = 0.0120 EC - 0.0004	0	0.00212
Gillman (1981)	I = 0.00446 EC - 0.000173	0	0.00919
Black and Campbell (1982)	I = 0.014 EC - 0.0002	0	0.00274

* A number of calculated values were negative.

The common feature for the Bungonia soils sampled is that the range for the empirical ionic strength values is much lower than those obtained by each of the previously mentioned researchers. This indicates that the Bungonia soils are likely to be highly dispersive, with the most dispersive soils (ESP > 15) being those with ionic strength close to zero. The application of the relationships in Table 5.1 is limited for the Bungonia soils because of the near zero values (in fact, some calculated values of ionic strength were negative) that are obtained and the poor relationship between the I/EC and ESP ($R^2 = 0.3887$).

Exchangeable aluminium is known to decrease the dispersibility of sodic soils and maintain the permeability of soil to water (Churchman *et al*, 1995). EAP was only greater than zero for certain sites at *Winston Gully*, ranging from 0–16%, a range which is considered non-toxic (Table 4.7). No significant relationship was observed between either EAP v ESP ($R^2 = 0.0425$) or EAP v pH ($R^2 = 0.2819$) (Table 4.11).

An interesting anomaly was soil sample 2B from *Winston Gully*, which had the highest ESP value of 47% (Table 4.7 and Plate 5.1). While such a high ESP value is indicative of highly dispersive soils, the sample actually flocculated in water. All other samples at *Winston Gully* which had high ESP values had no detectable exchangeable aluminium (Table 4.7). The fact that exchangeable aluminium (0.57 $cmol.kg^{-1}$) was present at site 2B could be the reason that the soil flocculated rather than dispersed since aluminium is known to resist dispersion. Other samples from *Winston Gully* (samples 1A, 3A, 4A, 5A, 5B and 6A) had exchangeable aluminium but did not flocculate. The exchangeable hydrogen appears to be the only variable that is significantly different between sample 2B (0.33 $cmol.kg^{-1}$) and the other samples (1.46 to 4.55 $cmol.kg^{-1}$).

The porosity of the soils decreases down the soil profile (see Table 4.1 to Table 4.3). The A horizons formed a hard surface crust upon drying, which is more resistant to erosion than the dispersive B horizons. A number of pinnacles have formed at *Winston Gully* due to the hardsetting A horizons providing a protective cap for the underlying horizons (Plate 4.3 and Plate 4.4).

In summary, the major characteristics contributing to the erosion observed at the study sites are:

- a hard setting, cracking permeable surface soil (A horizon) which provides direct access for surface water to enter the dispersive B horizon during rainfall events;
- an abrupt texture change between A and B horizons with a bleached A2;
- a high clay and silt content with a high ESP;
- sodic soils composed of highly dispersive clays (kaolinite and illite) in the B horizons; and
- a rainfall distribution pattern (intense at certain times and low on average) combined with a reduced ground cover.

Plate 5.1: The location where soil sample 2B (pink colour) was obtained at *Winston Gully*.

5.2 SEDIMENT YIELD OF WINSTON GULLY

It is difficult to obtain comparative rates for the sediment load and sediment yield of erosion gullies due to the variation in the manner which similar studies have been reported in the literature. Table 5.2 compares the sediment load and yield of *Winston Gully* to selected NSW creeks and gullies. From the table, it is obvious that both the sediment load and yield of *Winston Gully* is significantly higher than for other catchments. Based upon the description of each catchment, it is the high dispersibility of the soil, sparse vegetation cover and small catchment area which distinguishes *Winston Gully* from the other catchments.

While it is assumed that *Winston Gully* is contributing a high sediment load into Limekiln Creek, no study has been conducted to confirm whether sediment from *Winston Gully* actually reaches either Limekiln Creek or the Shoalhaven River, or is deposited beforehand. The sediment yield calculated for *Winston Gully* is based upon certain assumptions and approximations. Further studies need to be conducted over a number of years to confirm the calculated sediment yield, and to ascertain the periodicity of the sediment mobilised.

Table 5.2: Examples of NSW creeks and gully sediment loads.

Catchment	Area (km^2)	Mean Annual Rainfall (mm)	Total Sediment Load ($t.yr^{-1}$)	Sediment Yield ($t.km^{-2}.yr^{-1}$)
Congewai Creek (NSW)*	85.5	108.4	2 394	28
Deep Creek (NSW)*	25	764	3 025 - 5 800	121 - 232
Wimbledon Gully (NSW)#	-	620	1 100	-
Wellington Gully (NSW)#	-	620	990	-
Winston Gully (NSW)	≈1	670	3 800	3 800

* Data obtained from Rieger and Oliver (1988).
# Data obtained from Crouch and Blong (1989).

5.3 PREVIOUS AND CURRENT MANAGEMENT STRATEGIES

That prevention is better, and cheaper, than the cure is an often stated cliché. Some authors (Hudson, 1971) have even advocated that in certain circumstances the money, materials and effort should be directed towards preventing new erosion gullies from occurring rather than fixing existing gullies. Gully control is a difficult and expensive operation for land owners, with the cost of reclamation sometimes exceeding the value of the land. With the benefit of hindsight, the best chance to restrain *Winston Gully* was prior to the 1940s, before the gully head reached the highly dispersive soils that it currently occupies. Now, the goal is to arrest further erosion of the gully by stabilising the head and sidewalls.

Old tyres have been used with some success at *Inverary* to stabilise gullies which are shallow and without subsurface erosion (Plate 5.2). While the gully may be stabilised, the environmental consequences resulting from the breakdown of the tyres and the leaching of pollutants such as heavy metals and hydrocarbons is poorly understood. Further work needs to be done at this site to determine if pollutants are entering the soil and water table from the tyres. At Bungonia 2, a simple arch weir was constructed with the aim of controlling gully erosion (Plate 5.3). This attempt failed due to the dispersive nature of the soil, with the soil being eroded at the edges of the weir. Further work was abandoned and the erosion has continued unabated at this site.

The usual procedure in dealing with gully erosion is to retain the water at higher elevations as long as possible, allowing it to be absorbed by vegetation. This can be achieved by pastures, tree planting and contour furrows. Vegetation cover provides physical structure within the soil profile, reducing the velocity of the surface flow and the extent of scouring by increasing the hydraulic resistance. Some planting of trees has already been conducted on *Inverary* and *Inverary Park* around *Winston Gully*. However, where subsurface erosion is the dominant process, revegetation alone is unlikely to control the processes of gullying and tunnelling.

An investigation into the erosion at *Winston Gully* by Hart (1995) (ACT Forests) resulted in the following recommendations:

- The deep sandy soils should not require ripping or mounding.
- Areas where water logging occurs should be ripped and mounded.
- Ripping should be applied where there are either rooting restrictions or structured soils.

A program has commenced to plant the entire area surrounding *Winston Gully* with *Pinus radiata*. The goal of this scheme is to provide the landowners with an income from the plantation in the future, and to lower the water table, reducing the extent of subsurface erosion occurring at *Winston Gully*. Initially, the surrounding area was ripped and mounded along keylines, upon which the *Pinus radiata* were then planted. While the planting of pines has merit, ripping and mounding of the A horizon (Plate 1.1) is inadvisable. The trees should have been planted by alternative methods which do not disturb the soil profile in the manner that ripping and mounding does.

Keyline ripping and mounding is applicable when surface flow is the primary mechanism of erosion. The erosion occurring at the head of *Winston Gully* is primarily by subsurface processes rather than surface erosion. Surface water is pooled behind the keylines, which then seeps into the B horizon, resulting in greater dispersion and tunnelling within the soil. Additionally, the gully sidewall has been intersected at a number of places, resulting in new cracks within the soil profile (Plate 4.5). *Winston Gully* has already started to advance along these keylines which have intersected the gully walls.

Plate 5.2: Gully control along a dam wall at *Inverary*.

Plate 5.3: A previous attempt to control the problem of erosion by building an arch weir at Bungonia 2.

Sediment traps have been installed across the floor of *Winston Gully* by the Department of Land and Water Conservation Service (Goulburn) with the aim of decreasing the quantity of sediment entering Limekiln Creek. The sediment traps were initially successful, until the water flow was diverted around the traps due to the high dispersibility of the soil (Plate 5.4). This was similar to the effect observed at Bungonia 2, where a weir was previously constructed to control erosion. It is unlikely that the sediment traps will prove successful unless the sodium content of the soils is lowered.

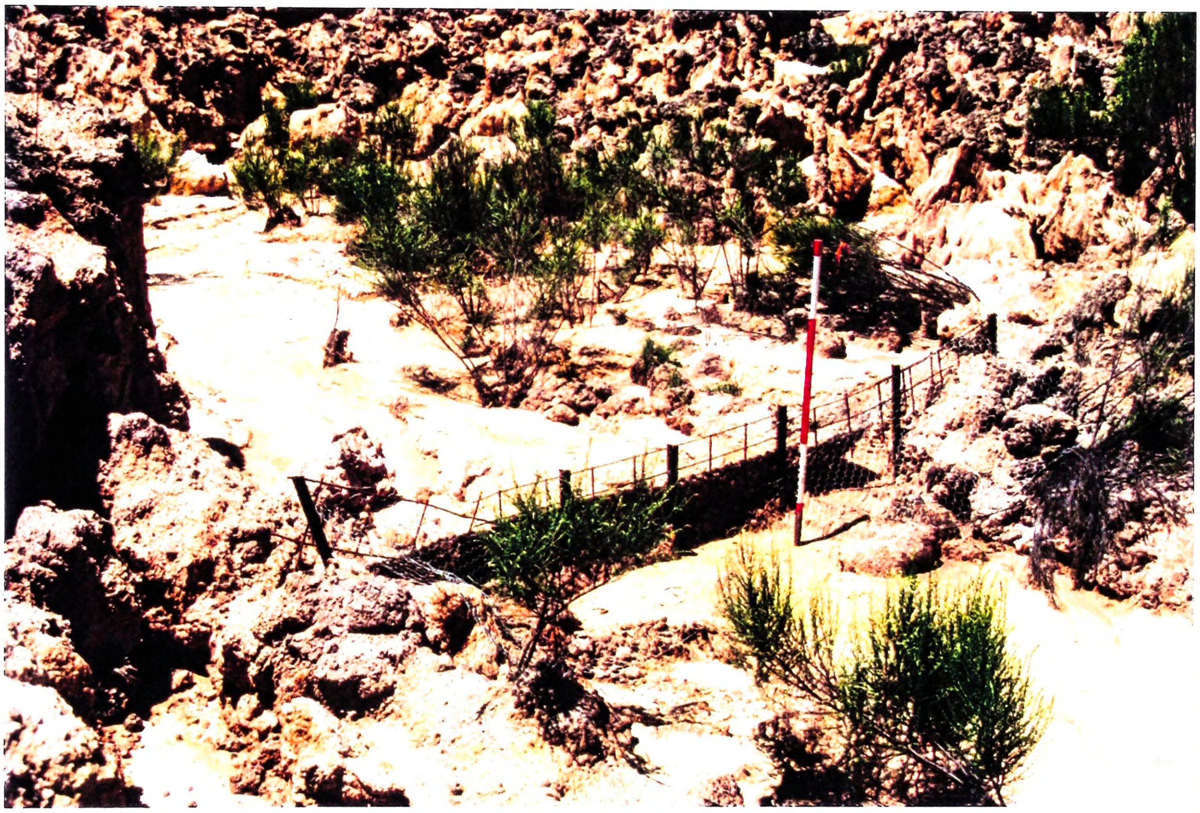

Plate 5.4: Sediment traps installed along the floor of *Winston Gully* to prevent the loss of sediment into Limekiln Creek.

Simple "physical" solutions such as keyline ripping, sediment traps and revegetation of the site will meet with only limited success unless the soil chemistry is also considered. The bonding between clay particles is weak due to the absence of cementing agents and weak covalent bonding between organic molecules and sodium. Rengasamy and Olsson (1991) reported that soils containing high concentrations of magnesium have a higher dispersive potential than soils which have higher concentrations of calcium. This is apparent at *Winston Gully*, where subsurface erosion is present when exchangeable sodium and magnesium are in high concentrations, but absent in areas of high calcium concentrations. A balance needs to be achieved in concentrations of the various cations in order to prevent swelling and dispersion of the clays. The most immediate requirement is to replace sodium with calcium. The behaviour of the constituent aluminosilicate minerals which are responsible for the loss of permeability of the soil need further investigation.

6 CONCLUSIONS AND FUTURE RECOMMENDATIONS

6.1 CONCLUSIONS

Gully and tunnel erosion are the result of surface and subsurface water movement in the soil profile, with European agricultural practices having greatly increased the extent and severity of soil erosion in Australia. The usual procedures in gully control includes the diversion of water above the gully, filling or reshaping of the gully, and establishing vegetation in gullies. However, these control measures are generally not applicable to areas affected by severe subsurface erosion. Recognition of the different sets of physical processes and a knowledge of gully morphology helps in the design of future soil conservation techniques.

The growth of *Winston Gully* has continued to accelerate, despite grazing stock having been excluded from the site since the mid-1980s. This is because the gully head is advancing primarily due to subsurface (tunnel) erosion rather than by surface flow related processes. Left unchecked, *Winston Gully* will probably stabilise when the gully head reaches the basalt slopes a further 200-300 m to the east. However, this is not a viable option, considering the area that the gully would probably cover by the time it eventually does stabilise. The present size and depth of the gully preclude gully control by filling and reshaping due to the expense. Only gully control methods which are inexpensive and relatively simple to implement are suitable for *Winston Gully*.

The adverse effects of dispersible clays on the soil physical properties are widely recognised. Numerous authors have reported that soil dispersibility depends on the nature of exchangeable cations, the ionic strength and electrical conductivity of the soil solution, clay type and texture, pH and organic matter. However, it was found that there was no significant association between most of these parameters at Bungonia. Only between TEB and CEC (R^2 = 0.984) did a significant association exist.

The sodicity of the soils at the three sites was determined in conjunction with ESP and field observations. The B horizons were identified as highly sodic due to the high exchangeable sodium content of the soils (Table 4.7 to Table 4.9). Sodic soils are known to have serious chemical, physical and nutritional problems (Sumner, 1993).

6.2 RE-EXAMINATION OF AIMS

- The extent and characteristics of contemporary processes of erosion were identified at the three sites. *Winston Gully* was the major study site, exhibiting severe subsurface erosion, fluting, pinnacle erosion and slumping as described in Chapter 4.

- The physical and chemical properties of the soils were analysed to determine various soil characteristics, identifying significant relationships between soil parameters and their influence on the processes of erosion. The statistical analysis for this study concluded that there was no significant relationship between the parameters tested except for TEB v CEC (Table 4.11).

- The erosion rate for *Winston Gully* was determined from aerial photographs and profile cross-sections conducted during 1995. The total quantity of sediment eroded from *Winston Gully* is approximately 200 000 t, with a sediment yield of 3 800 $t.km^{-2}.yr^{-1}$ (Table 4.13).

- Future soil management options of chemical and physical amelioration have been recommended in order to control the erosive processes. A review of previous and current management strategies were also examined.

6.3 FUTURE RECOMMENDATIONS

A recognition of the processes involved in the formation of gullying and tunnelling at Bungonia and other regions is critical in order to apply appropriate erosion control strategies. Where gully systems are influenced by subsurface erosion (e.g., *Winston Gully*), the traditional gully control methods aimed at reducing surface erosion are unlikely to be effective in controlling gully expansion.

Fitzpatrick *et al* (1995) stated that the soil conservation technique involving the ripping of the A horizon provides ready access for surface water to enter a dispersive subsoil. This can either initiate or aggravate tunnelling which may already be present. Controlling subsurface flow rather than surface runoff on the slopes surrounding *Winston Gully* is the major priority. By planting pines, crusting is alleviated by reducing the energy of impacting raindrops on the topsoil, and reducing the quantity of water from entering the subsurface horizons. Future research is needed to find appropriate soil management practices which are applicable to individual sites, rather than using a standard method to all sites. The use of inappropriate techniques will actually increase the erosion rather than control it.

Possible chemical and physical amelioration includes the following:

- The application of either lime (calcium carbonate) or gypsum (more soluble) to remove the sodium from the soil profile, and increase the strength of particle bonds by replacing the sodium. It is known from similar studies (McKenzie *et al*, 1993; Naidu *et al*, 1993; Rengasamy and Olsson, 1991) that gypsum prevents swelling and dispersion of soils, and stabilises soil aggregates by increasing the biological activity within the soil profile.

- Amelioration of sodic soils is usually based upon costly inorganic alteration and synthetic organic polymers. At lower costs, the use of naturally occurring soil biota (microbial organisms) and microbial reactions to control sodicity would appear to be more appropriate (Rengasamy and Olsson, 1991), and should be investigated further.

- Any further planting of pines should be conducted by methods which do not involve the large scale ripping of the soil profile.

- It is recommended that a water quality analysis be conducted on the rainwater and groundwater surrounding the catchment of *Winston Gully*. This would allow the sodium absorption ratio to be determined, and appropriate control measures applied in reducing the dispersibility of the soils.

REFERENCES

Aylmore, L.A.G. and Quirk, J.P. (1962). The structural status of clay systems. *Clays and Clay Mineralogy*, **9**, 185-208.

Barzegar, A.R., Murray, R.S., Churchman, G.J. and Rengasamy, P. (1994). The strength of remoulded soils as affected by exchangeable cations and dispersible clay. *Australian Journal of Soil Research*, **32**, 185-199.

Berry, L. (1970). Some erosional features due to piping and sub-surface wash with special reference to the Sudan. *Geografiska Annaler*, **52**, 113-119.

Black, A.S. and Campbell, A.S. (1982). Ionic strength of soil solution and its effect on charge properties of some New Zealand soils. *Journal of Soil Science*, **33**, 249-262.

Blakemore, L.C., Searle, P.L. and Daly, B.K. (1987). *Methods for Chemical Analysis of Soils.* New Zealand Soil Bureau Scientific Report 80, New Zealand.

Bocco, G. (1991). Gully erosion: processes and models. *Progress in Physical Geography*, **15**, 392-406.

Bocco, G. (1993). Gully initiation in Quaternary volcanic environments under temperate subhumid seasonal climate. *Catena*, **20**, 495-513.

Boucher, S.C. (1990). *Field Tunnel Erosion: its Characteristics and Amelioration.* Department of Conservation and Environment, Land Protection Division, Victoria and Monash University, Department of Geography and Environmental Science, Victoria.

Boucher, S.C. and Powell, J.M. (1994). Gullying and tunnel erosion in Victoria. *Australian Geographical Studies*, **32**, 17-26.

Bowyer-Bower, T.A.S. and Bryan, R.B. (1986). Rill initiation: concepts and experimental evaluation on badland slopes. *Zeitschrift für Geomorphologie N.F*, **60**, 161-175.

Bradford, J.M., Piest, R.F. and Spomer, R.G. (1978). Failure sequence of gully headwalls in Western Iowa. Division S-5 Soil genesis, morphology, and classification. *Soil Science Society of American Journal*, **42**, 323-328.

Bryan, R.H. and Yair, A. (1982). Perspectives on studies of badland geomorphology. In Bryan, R.H. and Yair, A. (ed.) *Badland Geomorphology and Piping.* Geo Books, England, pp1-12.

Bureau of Meteorology. (1988). *Climatic averages Australia.* Australian Government Publishing Service, Canberra.

Butzer, K.W. (1976). *Geomorphology from the Earth.* Harper and Row Publishers, New York.

Campbell, I.A. (1989). Badlands and badland gullies. In Thomas, D.S.G. (ed.) *Arid Zone Geomorphology*. Halsted Press, New York.

Charman, P.E.V. and Murphy, B.W. (1991). *Soils: their properties and management.* Sydney University Press in association with Oxford University Press, South Melbourne.

Chartres, C.J. (1993). Sodic soils: an introduction to their formation and distribution in Australia. *Australian Journal of Soil Research*, **31**, 751-760.

Chorom, M., Rengasamy, P. and Murray, R.S. (1994). Clay dispersion as influenced by pH and net particle charge of sodic soils. *Australian Journal of Soil Research*, **32**, 1243-1252.

Churchman, G.J., Skjemstad, J.O. and Oades, J.M. (1995). Effects of clay minerals and organic matter on sodicity. In Naidu, R., Sumner, M.E. and Rengasamy, P (ed.) *Australian Sodic Soils: Distribution, Properties and Management*, CSIRO, Melbourne, pp107-121.

Collis-George, N. and Lal, R. (1971). Infiltration and structural changes as influenced by initial moisture content. *Australian Journal of Soil Research*, **9**, 107-116.

Cooper, K. Land owner of *Inverary*. Personal Communication, 4th February 1996.

Craft, F. (1932). The physiography of the Shoalhaven River Valley. *Proceedings of the Linnean Society of New South Wales*, **57**, 245-260.

Crouch, R.J. (1976). Field tunnel erosion - a review. *Journal of Soil Conservation New South Wales*, **32**, 98-111.

Crouch, R.J. (1983). The role of tunnel erosion in gully head progression. *Journal of Soil Conservation New South Wales*, **39**, 148-155.

Crouch, R.J. and Blong, R.J. (1989). Gully sidewall classification: methods and applications. *Zeitschrift für Geomorphologie N.F*, **33**, 291-305.

Crouch, R.J., Dwyer, P.J. and Honeyman, M.N. (1987). Willows for gully erosion control in the Central Tablelands of NSW. *Journal of Soil Conservation New South Wales*, **43**, 28-31.

Crouch, R.J., Henry, R.A., O'Brien, W.J. and Sherlock, G. (1984). Small weirs for gully control. *Journal of Soil Conservation New South Wales*, **40**, 88-93.

Crouch, R.J., McGarity, J.W. and Storrier, R.R. (1986). Tunnel formation processes in the Riverina area of NSW. Australia. *Earth Surface Processes and Landforms*, **11**, 157-168.

CSIRO. (1983). *Soils: An Australian Viewpoint.* Academic Press, Melbourne.

Edwards, K., Blong, R.J. and Graham, O.P. (1989). Identification of sediment sources: implications for erosion control. *Australian Journal of Soil and Water Conservation*, **2**, 18-27.

Emerson, W.W. (1967). A classification of soil aggregates based on their coherence in water. *Australian Journal of Soil Research*, **5**, 47-57.

Eyles, R.J. (1977). Birchams Creek: the transition from a chain of ponds to a gully. *Australian Geographical Studies*, **15**, 146-157.

Fitzpatrick, R.W., Boucher, S.C., Naidu, R. and Fritsch, E. (1995). Environmental consequences of soil sodicity. In Naidu, R., Sumner, M.E. and Rengasamy, P (ed.) *Australian Sodic Soils: Distribution, Properties and Management*, CSIRO, Melbourne, pp163-177.

Floyd, E.J. (1974). Tunnel erosion-a field study in the Riverina. *Journal of Soil Conservation New South Wales*, **30**, 145-156.

Frenkel, F., Goetzen, J.O. and Rhoades, J.D. (1978). Effects of clay type and content, ESP, and electrolyte concentration on clay dispersion and soil hydraulic conductivity. *Soil Science Society of American Journal*, **42**, 32-39.

Gee, G.W. and Bauder, J.W. (1986). Particle size analysis. In Klute, A (ed.) *Methods of Soil Analysis Part 1:Physical and Mineralogical Methods*, American Society of Agronomy Inc. Soil Science Society of America Inc. Wisconsin.

Geonor A/S. H-60 Field Inspection Vane Tester, Instruction Manual, Norway.

Gillman, G.P. (1981). Effects of pH and ionic strength on the cation exchange capacity of soils with variable charge. *Australian Journal of Soil Research*, **19**, 93-96.

Gillman, G.P. and Bell, L.C. (1978). Soil solution studies on weathered soils from tropical North Queensland. *Australian Journal of Soil Research*, **16**, 67-77.

Graham, O.P. (1984). Gully erosion. *Journal of Soil Conservation New South Wales*, **40**, 31-37.

Hart, D.C. (1995). *Soil Survey of Mr. P Broadhead's Property, Bungonia, New South Wales.* ACT Forests, MASO-05.

Harvey, A.M. (1992). Process interactions, temporal scales and the development of hillslope gully systems: Howgill Fells, northwest England. *Geomorphology*, **5**, 323-344.

Heede, B.H. (1974). Stages of development of gullies in Western United States of America. *Zeitschrift für Geomorphologie N.F*, **18**, 260-271.

Heede, B.H. and de Bano, L.F. (1984). Gully rehabilitation - a three-stage process in a sodic soil. *Soil Science Society of American Journal*, **48**, 1416-1422.

Hudson, N. (1971). *Soil Conservation.* B.T Batsford Limited, London.

Hughes, P.J. and Sullivan, M.E. (1981). Aboriginal burning and late Holocene geomorphic events in Eastern N.S.W. *Search*, **12**, 277-278.

Hutchinson, C.S. (1974). Laboratory Handbook of Petrographic Techniques, John Wiley and Sons, New York.

Jones, A. (1971). Soil piping and stream channel initiation. *Water Resources Research*, **7**, 602-610.

Kooringaroo 8828-11-S. Topographic Map 1:25 000 Second Edition. NSW.

Ku, P.A. (1995). Sodium exchange characteristics of some Australian soils. Unpublished Honours Master of Environmental Science Thesis, University of Wollongong, Wollongong.

Leeper, G.W. (1967). *Introduction to Soil Science.* Melbourne University Press, Victoria.

Martin-Penela, A.J. (1994). Pipe and gully systems development in the Almanzora Basin (Southeast Spain). *Zeitschrift für Geomorphologie N.F*, **38**, 207-222.

McDonald, R.C., Isbell, R.F., Speight, J.G., Walker. J. and Hopkins, M.S. (1990). *Australian Soil and Land Survey: Field Handbook.* Inkata Press, Melbourne.

McKenzie, D.C., Abbott, T.S., Chan, K.Y., Slavich, P.G. and Hall, D.J.M. (1993). The nature, distribution and management of sodic soils in New South Wales. *Australian Journal of Soil Research*, **31**, 839-868.

Naidu, R. and Rengasamy, P. (1995). Ion interactions and constraints to plant nutrient in Australian sodic soils. In Naidu, R., Sumner, M.E. and Rengasamy, P (ed.) *Australian Sodic Soils: Distribution, Properties and Management*, CSIRO, Melbourne, pp127-139.

Naidu, R., Sumner, M.E. and Rengasamy, P. (1993). National conference on sodic soils: summary and conclusions. *Australian Journal of Soil Research*, **31**, 949-956.

Naylor, G.F.K. (1950). A further contribution to the geology of the Goulburn District, New South Wales. *Journal of the Proceedings of the Royal Society of New South Wales*, **83**, 279-287.

Newman, J.C. and Phillips, J.R.H. (1957). Tunnel erosion in the Riverina. *Journal of Soil Conservation New South Wales*, **13**, 159-169.

Northcote, K.H. and Skene, J.K.M. (1972). *Australian soils with saline and sodic properties.* CSIRO Australia. Soil Publication 27.

de Oliveira, M.A.T. (1989). Erosion disconformities and gully morphology: A three dimensional approach. *Catena*, **16**, 413-423.

Packham, G.H. (1969). The geology of New South Wales. *Journal of the Geological Society of Australia*, **16**, 1-654.

Poesen, J. and Govers, G. (1990). Gully erosion in the Loam Belt of Belgium: Typology and control measures. In Boardman, J., Foster, I.D.L. and Dearing, J.A. (ed.) *Soil Erosion on Agricultural Land*, John Wiley and Sons, Chichester, pp513-530.

Prosser, I.P. (1991). A comparison of past and present episodes of gully erosion at Wangrah Creek, Southern Tablelands, New South Wales. *Australian Geographical Studies*, **29**, 139-154.

Pyrde, G. Department of Land and Water Conservation Service New South Wales, Goulburn Office. Personal Communication, 12th April 1995.

Rayment, G.E. and Higginson, F.R. (1992). *Australian Laboratory Handbook of Soil and Water Chemical Methods*. Inkata Press, Melbourne.

Rengasamy, P. (1983). Clay dispersion in relation to changes in the electrolyte composition of dialysed red-brown earths. *Journal of Soil Science*, **34**, 723-732.

Rengasamy, P. and Olsson, K.A. (1991). Sodicity and soil structure. *Australian Journal of Soil Research*, **29**, 935-952.

Rieger, W.A. and Oliver, L.J. (1988). Channel sediment loads: comparisons and estimation. In Warner, R.F. (ed). *Fluvial Geomorphology of Australia*. Academic Press, Sydney, pp69-85.

Schouten, C.J. and Rang, M.C. (1984). Measurement of gully erosion and the effects of soil conservation techniques in Puketurua Experimental Basin (New Zealand). *Zeitschrift für Geomorphologie N.F*, **49**, 151-164.

Smith, B.J. (1982). Effects of climate and land-sue change on gully development: An example from Northern Nigeria. *Zeitschrift für Geomorphologie N.F*, **14**, 33-51.

So, H.B. and Aylmore, L.A.G. (1993). How do sodic soils behave? The effects of sodicity on soil physical behaviour. *Australian Journal of Soil Research*, **31**, 761-777.

Sumner, M.E. (1993). Sodic soils: New perspectives. *Australian Journal of Soil Research*, **31**, 683-750.

Swanson, M., Kondolf, G.M. and Boison, P.J. (1989). An example of rapid gully initiation and extension by subsurface erosion: Coastal San Mateo county, California. *Geomorphology*, **2**, 393-403.

Thomas, R.F. (1981). Soil Bureau, D.S.I.R. Institute of Applied Sciences, Analytical Laboratory, New Zealand.

Thompson, L.M. and Troeh, F.R. (1973). *Soils and Soil Fertility.* McGraw-Hill Book Co, New York.

Tisdall, J.M. and Oades, J.M. (1982). Organic matter and water-stable aggregates in soils. *Journal of Soil Science*, **33**, 141-163.

Trzcinka, B.W; Loughran, R.J. and Campbell, B.L. (1993). The geomorphology of a field tunnel system: A case study from Australia. *Zeitschrift für Geomorphologie N.F*, **37**, 237-247.

Veness, J.A. (1980). The role of fluting in gully extension. *Journal of Soil Conservation of New South Wales*, **36**, 100-108.

Wellman, P. (1974). Potassium-Argon ages on the Cainozoic volcanic rocks of Eastern Victoria, Australian. *Journal of the Geological Society of Australia*, **21**, 359-376.

Wray, R.A.L. (1991). *The Morphology and Development of a Cainozoic Landscape at Bungonia, New South Wales Southern Highlands.* Bachelor of Science (Honours) Thesis, University of Wollongong, Wollongong.

Wray, R.A.L., Young, R.W. and Price, D.M. (1993). Cainozoic heritage in the modern landscape near Bungonia, Southern New South Wales. *Australian Geographer*, **24**, 45-61.

Young, R.W., Nanson, G.C. and Bryant, E.A. (1986). Alluvial chronology for coastal New South Wales. Climatic control or random erosional event? *Search*, **17**, 270-272.

Yuan, T.L. (1959). Determination of exchangeable hydrogen in soils by a titration method. *Soil Science*, **88**, 164-167.

Zachar, D. (1982). *Soil Erosion: Development in Soil Science 10.* Elsevier Scientific Publishing Company, Amsterdam.

APPENDICES

A.1 PEDON WINSTON GULLY

Site 1

Horizon	Depth (cm)	Description
A2	0-25	dry; light grey (10YR 6/1); dispersed common medium subrounded pebbles; lithology unknown; many very fine roots; firm to moderate consistence; fine cracks; common fine macropores and abrupt smooth boundary.
A3	25-50	moderately moist; light olive grey (5Y 6/2); slightly sticky; firm to moderate consistence; absent of voids and pores with a gradual undefined boundary shape.
B21	50-130	moderately moist; pale yellow (2.5Y 8/4); 20-50% coarse distinct mottles; non-sticky; firm to moderate consistence; absent of voids and pores; coarse rocks on the outer surface; gradual smooth boundary.
B22	130-330	dry; pale yellow (2.5Y 8/4); 20-50% coarse distinct mottles; very few (<2%) rounded and angular fragments consisting of a mixture of large pebbles and cobbles dispersed throughout the horizon; carbonate nodules present; very firm consistence; fine cracks present; gradual smooth boundary.
B23	330-500	dry; yellow (10YR 7/6); many very coarse distinct colour patterns due to inclusions of weathered substrate material; 20-50% small rounded dispersed pebbles; very firm consistence; fine cracks; many very fine macropores.

Site 2

Horizon	Depth (cm)	Description
A2	0-15	dry; light brownish grey (10YR 6/2); 10-20% medium faint mottles; common small rounded dispersed pebbles; common very fine grass roots; firm strength; fine cracks; very fine macropores; gradual smooth boundary.
A3	15-25	dry; dark brown (10YR 3/3); 20-50% medium faint mottles; many dispersed small rounded tabular pebbles; few very fine roots; very strong consistence; fine cracks; few very fine macropores; gradual smooth boundary.
B1	25-105	dry; brown (10YR 5/3); 20-50% very coarse faint mottles; abundant (50-90%) small rounded tabular pebbles dispersed; few very fine roots; very strong consistence; fine cracks; no fine or coarse macropores; gradual smooth boundary.
B2	105-160	dry; yellow (10YR 7/6); very few (<2%) medium angular stratified pebbles; no root material present; very strong consistence; fine cracks; no fine or coarse macropores.

A.2 PEDON BUNGONIA 2

Site 1

Horizon	Depth (cm)	Description
A1	0-20	very dry; light grey (10YR 6/1); coarse fragments and mottles absent; strong strength; slightly sticky; fine cracks; many very fine macropores; common medium roots; clear wavy boundary distinctness.
A2	20-30	dry; dark brown (10YR 2/2); abundant (50-90%) coarse (20-60 mm) angular fragments; common medium roots; strong strength; slightly sticky; fine cracks; many very fine macropores; clear wavy boundary distinctness.
B2	30-300	dry; greyish brown (10YR 5/2); 20-50% coarse distinct mottles; abundant (50-90%) coarse (20-60 mm) angular and rounded stratified fragments; medium cracks; fine macropores; strong strength; remains of old roots present.

Site 2

Horizon	Depth (cm)	Description
A1	0-35	dry; dark greyish brown (10YR 4/2); 2-10% coarse gravelly angular and tabular stratified fragments; many very fine roots; very firm strength; few fine (1-2 mm) cracks; abrupt smooth boundary.
B1	35-100	dry; strong brown (7.5YR 5/8); common medium sized distinct mottles; abundant (50-90%) coarse gravelly angular fragments dispersed within the horizon; strong consistence; no cracks present; many very fine macropores; diffuse smooth boundary.
B2	100-300	dry; pale yellow (2.5Y 8/3); 20-50% very coarse distinct mottles; many coarse gravelly rounded and angular mixture of dispersed fragments; very strong consistence; fine cracks with a few fine macropores.

A.3 PEDON BUNGONIA 3

Site 1

Horizon	Depth (cm)	Description
A1	0-20	very dry; light brownish grey (2.5Y 6/2); 2-10% medium gravelly angular and tabular stratified fragments; few fine roots; strong consistence; few fine (1-2 mm) cracks; abrupt smooth boundary.
B1	20-110	very dry; strong brown (7.5YR 5/6); many medium sized distinct mottles; abundant (50-90%) coarse gravelly angular fragments dispersed within the horizon; strong consistence; many very fine macropores; diffuse smooth boundary.
B2	110-250	very dry; pale yellow (2.5Y 8/3); 20-50% very coarse distinct mottles; many coarse gravelly rounded and angular mixture of dispersed fragments; very strong consistence; fine cracks with a few fine macropores.

A.4 ATOMIC ABSORPTION SPECTROMETER DATA FOR WINSTON GULLY

Absorbance of Ca^{2+}

Site	Horizon	Atomic Absorption				St. Relative Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	A	0.062	0.061	0.059	0.061	1.9	1.48
	B	0.057	0.055	0.056	0.056	1.2	1.37
	C	0.201	0.192	0.196	0.196	2.1	4.87
2	A	0.228	0.221	0 214	0.221	3.2	5.50
	B	0.175	0.180	0.181	0.178	1.6	4.42
3	A	0.068	0.066	0.067	0.067	1.5	1.64
	B	0.060	0.059	0.059	0.059	0.5	1.44
4	A	0.261	0.257	0.256	0.258	1.1	6.48
	B	0.165	0.161	0.165	0.163	1.5	4.04
5	A	0.353	0.351	0.353	0.353	0.3	9.08
	B	0.463	0.451	0.459	0.458	1.4	11.76
6	A	0.438	0.432	0.435	0.435	0.8	11.22
	B	0.771	0.766	0.780	0.773	0.9	21.03

Absorbance of Mg^{2+}

Site	Horizon	Atomic Absorption				St. Relative Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	A	0.342	0.341	0.344	0.342	0.4	1.14
	B	0.027	0.027	0.025	0.026	4.2	11.3
	C	0.075	0.071	0.069	0.071	4.0	2.56
2	A	0.212	0.219	0.215	0.215	1.7	7.77
	B	0.014	0.015	0.011	0.013	13.9	5.7
3	A	0.115	0.112	0.110	0.112	2.0	4.02
	B	0.031	0.027	0.027	0.028	9.2	12.2
4	A	0.255	0.259	0.254	0.256	1.0	9.26
	B	0.031	0.034	0.033	0.033	4.6	14.1
5	A	0.165	0.168	0.169	0.167	1.3	6.01
	B	0.046	0.053	0.048	0.049	7.6	20.8
6	A	0.343	0.354	0.352	0.350	1.7	12.78
	B	0.095	0.095	0.096	0.095	0.5	41.7

Absorbance of K^+

Site	Horizon	Atomic Absorption				St. Relative Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	A	0.431	0.434	0.439	0.435	0.9	9.45
	B	0.238	0.237	0.239	0.238	0.4	4.64
	C	0.180	0.181	0.180	0.180	0.5	3.18
2	A	0.107	0.103	0.104	0.105	1.7	1.52
	B	0.483	0.482	0.489	0.485	0.7	10.80
3	A	0.385	0.386	0.385	0.386	0.2	8.19
	B	0.292	0.289	0.288	0.290	0.7	5.90
4	A	0.113	0.112	0.114	0.113	0.8	1.63
	B	0.224	0.225	0.224	0.225	0.3	4.28
5	A	0.098	0.098	0.098	0.098	0.4	1.42
	B	0.413	0.410	0.412	0.412	0.4	8.86
6	A	0.254	0.257	0.256	0.256	0.7	4.32
	B	0.435	0.431	0.432	0.433	0.4	9.40

Absorbance of Na^+

Site	Horizon	Atomic Absorption				St. Relative Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	A	0.069	0.068	0.068	0.069	1.0	2.6
	B	0.580	0.580	0.581	0.580	0.2	23.3
	C	0.477	0.482	0.481	0.480	0.5	18.8
2	A	0.466	0.465	0.469	0.467	0.5	18.3
	B	0.351	0.353	0.358	0.354	1.1	13.5
3	A	0.695	0.697	0.703	0.698	0.6	28.8
	B	0.656	0.659	0.660	0.658	0.3	26.9
4	A	0.316	0.314	0.314	0.315	0.4	11.9
	B	0.497	0.501	0.503	0.500	0.6	19.7
5	A	0.011	0.011	0.012	0.011	4.6	0.4
	B	0.094	0.094	0.092	0.094	1.3	3.5
6	A	0.087	0.087	0.085	0.086	0.8	3.2
	B	0.063	0.064	0.065	0.064	1.3	0.80

A.5 ATOMIC ABSORPTION SPECTROMETER DATA FOR BUNGONIA 2

Absorbance of Ca^{2+}

Site	Horizon	Atomic Absorption				St. Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	B	0.239	0.242	0.246	0.242	1.5	6.06
2	B	0.311	0.311	0.302	0.308	1.7	7.82
3	B	0.671	0.666	0.650	0.662	1.6	16.98
4	B	0.733	0.726	0.727	0.729	0.6	19.37
5	A	0.502	0.495	0.504	0.500	0.9	12.77
	B	0.507	0.500	0.499	0.502	0.8	12.81
6	B	0.389	0.387	0.385	0.387	0.5	10.06

Absorbance of Mg^{2+}

Site	Horizon	Atomic Absorption				St. Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	B	0.174	0.173	0.177	0.175	1.4	6.28
2	B	0.030	0.032	0.034	0.032	5.8	13.8
3	B	0.045	0.051	0.047	0.048	6.5	20.4
4	B	0.418	0.418	0.410	0.415	1.1	15.31
5	A	0.066	0.064	0.066	0.065	1.1	28.1
	B	0.211	0.202	0.206	0.206	2.2	7.44
6	B	0.018	0.023	0.019	0.020	12.5	8.7

Absorbance of K^{+}

Site	Horizon	Atomic Absorption				St. Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	B	0.416	0.428	0.420	0.412	1.4	9.10
2	B	0.345	0.348	0.346	0.346	0.6	7.22
3	B	0.098	0.098	0.098	0.098	0.0	1.42
4	B	0.149	0.149	0.148	0.149	0.7	2.18
5	A	0.126	0.127	0.128	0.127	0.9	1.84
	B	0.335	0.334	0.337	0.335	0.4	6.96
6	B	0.220	0.220	0.219	0.220	0.5	4.15

Absorbance of Na^+

Site	Horizon	Atomic Absorption				St. Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	B	0.399	0.396	0.394	0.396	0.6	15.3
2	B	0.402	0.403	0.401	0.402	0.2	15.5
3	B	0.730	0.720	0.718	0.722	0.9	29.9
4	B	0.360	0.363	0.367	0.364	0.9	13.9
5	A	0.465	0.469	0.469	0.468	0.6	18.3
	B	0.894	0.891	0.891	0.892	0.2	38.4
6	B	0.728	0.731	0.730	0.730	0.2	30.3

A.6 ATOMIC ABSORPTION SPECTROMETER DATA FOR BUNGONIA 3

Absorbance of Ca^{2+}

Site	Horizon	Atomic Absorption				St. Relative Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	A	0.563	0.565	0.565	0.564	0.2	14.25
	B	0.652	0.650	0.639	0.647	1.1	16.48
2	A	0.068	0.068	0.067	0.068	0.8	1.65
	B	0.162	0.161	0.160	0.161	0.5	3.98
	C	0.070	0.070	0.069	0.070	1.1	1.71

Absorbance of Mg^{2+}

Site	Horizon	Atomic Absorption				St. Relative Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	A	0.053	0.055	0.057	0.055	3.7	23.7
	B	0.077	0.084	0.077	0.079	5.0	34.4
2	A	0.015	0.014	0.011	0.013	14.1	0.48
	B	0.198	0.202	0.199	0.200	0.9	7.20
	C	0.018	0.022	0.015	0.018	20.1	7.8

Absorbance of K^{+}

Site	Horizon	Atomic Absorption				St. Relative Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	A	0.100	0.100	0.100	0.100	0.3	1.44
	B	0.392	0.392	0.387	0.390	0.8	8.31
2	A	0.128	0.127	0.127	0.127	0.4	2.05
	B	0.450	0.453	0.449	0.450	0.5	9.87
	C	0.225	0.228	0.226	0.226	0.5	4.33

Absorbance of Na^+

Site	Horizon	Atomic Absorption				St. Relative Dev (%)	Concentration ($mg.L^{-1}$)
		Reading 1	Reading 2	Reading 3	Mean		
1	A	1.134	1.145	1.134	1.138	0.5	51.8
	B	0.427	0.429	0.424	0.427	0.7	16.5
2	A	0.024	0.023	0.022	0.023	4.1	0.9
	B	0.702	0.698	0.699	0.700	0.3	28.9
	C	1.736	1.767	1.752	1.751	0.9	100.1

A.7 SHEAR STRENGTH TESTING AND SOIL MOISTURE CONTENT DATA FOR WINSTON GULLY

Date	Sample	Horizon	Sampling Depth (m)	Mean Soil Moisture Content (%)	Mean Shear Strength Testing ($t.m^{-2}$)
1/4/95	1	A	0.07	2.5	17.5
		B	0.75	2.4	N/A
		C	5.00	6.4	4.10
	2	A	0.10	3.5	23.2
		B	5.50	4.9	N/A
	3	A	0.05	0.5	N/A
		B	6.00	1.1	N/A
	4	A	0.10	0.6	23.6
		B	9.00	4.8	N/A
	5	A	0.07	4.6	22.1
		B	1.70	4.1	15.8
	6	A	0.07	1.1	N/A
		B	3.00	5.8	5.7
21/6/95	1	A	0.15	15.3	4.0
		B	0.80	4.3	N/A
		C	N/A	N/A	N/A
	2	A	0.40	3.0	N/A
		B	0.50	7.3	3.9
	3	A	N/A	N/A	N/A
		B	N/A	N/A	N/A
	4	A	N/A	N/A	N/A
		B	3.00	15.4	8.1
	5	A	0.14	15.3	3.1
		B	1.10	10.3	3.1
	6	A	0.17	3.2	4.4
		B	3.75	4.3	N/A

A.8 GENERAL CHEMICAL ANALYSIS ON SOILS AT WINSTON GULLY

A Horizons

Site	$CaCO_3$		Soluble Carbonate		Soluble Sulphates		Soluble Chlorides		Organic Matter	
	P	A	P	A	P	A	P	A	P	A
1		√		√		√		√	√	
2		√		√		√		√	√	
3		√		√		√		√	√	
4		√		√		√		√	√	
5		√		√		√		√	√	
6		√		√		√		√	√	

Note: P indicates present and A indicates absent.

B Horizons

Site	$CaCO_3$		Soluble Carbonate		Soluble Sulphates		Soluble Chlorides		Organic Matter	
	P	A	P	A	P	A	P	A	P	A
1		√		√		√	√			√
2		√		√		√	√			√
3		√		√		√	√			√
4		√		√		√	√			√
5		√		√		√		√	√	
6		√		√		√		√	√	

Note: P indicates present and A indicates absent.

A.9 GENERAL CHEMICAL ANALYSIS ON SOILS AT BUNGONIA 2

A and B Horizons

Site	Location	$CaCO_3$		Soluble Carbonate		Soluble Sulphates		Soluble Chlorides		Organic Matter	
		P	A	P	A	P	A	P	A	P	A
1	B		√		√		√	√		√	
2	B		√		√		√	√		√	
3	B		√		√		√	√		√	
4	B		√		√		√		√	√	
5	A		√		√		√		√	√	
	B		√		√		√		√	√	
6	B		√		√		√	√		√	

Note: P indicates present and A indicates absent.

A.10 GENERAL CHEMICAL ANALYSIS ON SOILS AT BUNGONIA 3

A, B and C Horizons

Site	Horizon	$CaCO_3$		Soluble Carbonate		Soluble Sulphates		Soluble Chlorides		Organic Matter	
		P	A	P	A	P	A	P	A	P	A
1	A		√		√		√		√	√	
	B		√		√		√		√	√	
2	A		√		√		√		√	√	
	B		√		√		√		√		√
	C		√		√		√	√			√

Note: P indicates present and A indicates absent.

A.11 TUNNEL AREA CALCULATIONS AT WINSTON GULLY

Site	Width (m)	Height (m)	Area (ellipse) m^2
S1	0.40	0.60	0.189
	0.50	0.25	0.098
	0.25	0.50	0.098
	0.35	0.30	0.082
	0.20	0.30	0.047
	0.30	0.10	0.094
	0.50	0.20	0.079
S2	0.15	0.25	0.029
	0.50	1.00	0.393
	0.15	0.10	0.012
S5	0.15	0.10	0.012
	0.20	0.15	0.024
	0.50	0.15	0.059
S11	0.30	0.15	0.035
S25	0.10	0.10	0.008
	0.10	0.20	0.016
	0.10	0.15	0.012
S26	0.05	0.05	0.002
	0.20	0.05	0.008
S27	0.15	0.25	0.029
	0.50	0.50	0.196
	0.10	0.05	0.004
	0.05	0.10	0.004
S30	0.40	0.30	0.094
	0.15	0.20	0.024
	0.50	0.75	0.295
	0.40	0.50	0.157

D.B. AITCHISON
BOOKBINDER
122 WINDANG RD.
PRIMBEE 2502
PH (042) 742229